

(NASA-CR-160558) DEVELOPMENT OF A COMPOSITE
GEODETIC STRUCTURE FOR SPACE CONSTRUCTION
PHASE 1A (McDonnell-Douglas Astronautics
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DEVELOPMENT OF A COMPOSITE GEODETIC
STRUCTURE FOR SPACE CONSTRUCTION
PHASE 1A FINAL REPORT

MCDONNELL
DOUGLAS
CORPORATION

31 JANUARY 1980

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PREPARED FOR: NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
JOHNSON SPACE CENTER
HOUSTON, TEXAS

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PREFACE

This report was prepared by the McDonnell Douglas Astronautics Company (MDAC) for the National Aeronautics and Space Administration-Johnson Space Center (NASA-JSC) in accordance with contract NAS9-15678, DRL No. T-1522, DRD No. MA-201 TB, Line Item No. 3. It documents the results of Phase 1A of a three phase program entitled, "Development of a Composite Geodetic Structure for Space Construction," which has as its major objective the development of a geodetic beam and beam fabrication machine, i.e., beam builder, for on-orbit construction of large truss-type space structures. The results of the Phase 1A program were generated from 1 September 1979 through 31 January 1980. The Phase 1A activities supplemented Phase 1 and provided required additional investigations addressing local shell attachment concepts, high temperature extruded rod material, and encapsulated joints capable of high temperature service.

Overall project responsibility for the Development of a Composite Geodetic structure for Space Construction program was assigned to the MDAC Engineering Division, Research and Development directorate, responsible for all engineering studies and experimental activities. Supervisory authority for the project was given to Dr. J. F. Garibotti, Chief Technology Engineer - Research and Development - Structures and Materials, who reported to R. F. Zemer, Director - Structures and Materials, on all study-related matters. Mr. A. J. Cwiertny was Program Manager and also provided technical support to the program. Mr. R. Johnson was Principal Investigator, responsible for coordinating all technical activities of the program. During the Phase 1A program, subcontract support was provided by the Compositek Engineering Corporation (CEC) of Buena Park, California. Dr. Brian Jones, President of Compositek, reported directly to Mr. Cwiertny for coordinating Compositek activities.

The scope of this program was very broad and included many individuals who provided technical support. MDAC and CEC personnel who significantly

contributed to this program during Phase 1A include:

Structural Design: J. Sagata and J. F. Dubel

Structural Analysis: M. H. Schneider and Dr. C. D. Babcock (Consultant)

Materials and Processes: V. L. Freeman, D. Waldehaar (CEC),

F. J. Schneider, P. J. Miller, and M. Vasca

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Section 1

INTRODUCTION AND SUMMARY

1.1 INTRODUCTION

Recent studies of future large space systems, such as space platforms, phased arrays, antennas, and solar power satellites, have substantiated the requirement for technology developments which will lead to on-orbit fabrication and assembly of large structural subsystems. In recognition of the need for an on-orbit fabrication capability, the NASA Johnson Space Center initiated a three-phase program in late 1978 with the overall objective of developing a geodetic beam and beam fabrication machine, i.e., beam builder for on-orbit construction of large truss type space structures. The geodetic beam, originally proposed by T. J. Dunn of NASA in 1976, is a lightweight, open lattice structure composed of an equilateral gridwork of criss-crossing rods. This beam provides a high degree of stiffness and minimizes structural distortion, due to temperature gradients, through the incorporation of a new graphite and glass reinforced thermoplastic composite material with a low coefficient of thermal expansion. A low power consuming, high production rate, beam builder automatically fabricates the geodetic beams in space using rods preprocessed on earth (Figure 1-1).

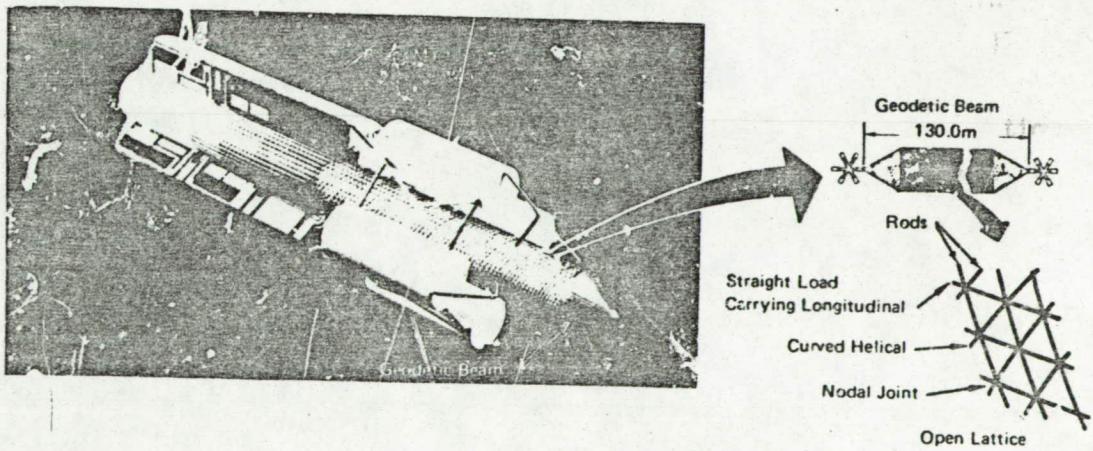


Figure 1-1. Geodetic Beam and Beam Builder.

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1.2 SUMMARY

The overall objective of this program is to develop a structurally efficient composite geodetic beam and a beam fabrication machine for on-orbit construction of large space structures. The program efforts are divided into three phases with each phase scheduled for approximately one year in duration. Phase I, initiated on 24 August 1979, consisted of tasks to (1) develop structural design requirements, (2) develop analytical procedures and select the best configuration for a geodetic beam, (3) develop structural termination concepts for the geodetic beam, (4) accomplish beam preliminary sizing, (5) develop pultruded composite rod stock for use in joining tests and feasibility test articles, (6) select a reliable joining technique, (7) design, fabricate, and test two geodetic test articles to establish concept feasibility, and initiate the preliminary design of a beam fabrication machine. Additional Phase I efforts consisted of preparation of an Orbital Flight Test (OFT) plan and fabrication of a scale model to demonstrate a key subsystem of the geodetic beam machine. Phase II will be devoted to detailed material characterization tests of the pultruded composite rods and encapsulated joints, parameter tests of a geodetic test cylinder and a cylinder/conical closeout test article, and an improved geodetic beam analysis based on the parameter tests. The tasks (Tasks 11 and 12) of Phase II have been deferred. Task 11 is the verification tests of full scale test articles and Task 12 is the completion of the beam machine design. Completion of Tasks 11 and 12, especially Task 12, will provide a sound basis for the work to be conducted in Phase III. It is therefore recommended that Tasks 11 and 12 be conducted prior to the start of ground demonstrations of beam fabrication in Phase III. In Phase III, the ground demonstration of automatic fabrication of geodetic beams will be accomplished using pilot-plant equipment capable of automatically fabricating demonstration articles.

To assure a highly qualified source for development material, MDAC subcontracted pultruded rod stock material fabrication to the Compositek Engineering Corporation (CEC) of Buena Park, California, a subsidiary of the Kelsey-Hayes Company which has extensive experience in pultruding

graphite-thermoplastic composite shapes. Pultruded rod stock fabricated by CEC from HMS/P1700 prepreg material was used in a majority of joining trials and in fabricating test cylinders during Phase I. High temperature graphite/polyimide rod stock was also produced by CEC during Phase IA.

As indicated previously, each phase of the program was initially planned as a 12-month effort. However, as Phase I neared completion it became apparent that additional effort in three areas would be beneficial before starting Phase II. Those three areas are (1) geodetic beam designs for local attachment of equipment or beam-to-beam joining in parallel or crossing configurations, (2) evaluation of long-life pultruded rods capable of service temperatures higher than possible with the HMS/P1700 rod material, and (3) evaluation of high temperature joint encapsulant materials. Thus, Phase IA was initiated to supplement Phase I investigations in the three identified task areas. The extended Phase I tasks are Tasks 2, 5, and 6. The additional work under those tasks (designated Tasks 2a, 5a, and 6a) is summarized as follows:

- Task 2a addressed local shell attachment designs. The objective of this task was to develop design concepts for attachment of secondary structure or equipment and to develop concepts for geodetic beam-to-geodetic beam joining without use of termination concepts. In addition, large truss assembly configurations using side-by-side joining methods were investigated.
- Under Task 5a, the objective was to pultrude a high temperature graphite thermoplastic rod material using a resin system such as NR150A2 polyimide, and to evaluate coatings or additive materials that are capable of minimizing the effects of space environment. After completion of Task 5a, notification was received from duPont that the NR150 series resin systems would no longer be available due to the slow development of a market for those resins.
- In Task 6a, the objective was to evaluate encapsulated joints capable of high temperature service for use with the rod stock produced in Task 5a.

The results of Phase IA, covering the period from 1 September 1979 to 31 January 1980, are reported herein.

Section 2

GEODETIC BEAM LOCAL ATTACHMENTS

The initial design of the geodetic beam focused on use of the beam as truss members in a tetrahedral truss or similar truss type configuration in which the beams were joined at their ends. Thus, early design efforts emphasized comparison of closeout designs at beam ends and node fittings where the members intersected. Additional attachment requirements will be needed in orbital structures, such as platforms and antennas, to attach equipment, cables, electrical harnesses, propulsion units, and scientific experiments. Also, structural arrangements other than tetrahedral trusses will require the joining of beams in parallel arrangements or overlapping arrangements where beams cross each other. Design arrangements for making local attachments and for joining beams without using end closeouts (normally used in intersecting configurations) were therefore studied in Phase IA, and design concepts were generated to satisfy local attachment requirements.

Structural arrangements and design problems that were considered in deriving attachment configurations are listed below:

1. Beam-to-beam parallel attachments.
2. Beam end-to-node point fitting.
3. Beam-to-beam tee intersections (overlap and butt).
4. Cable attachments to beam.
5. Propulsion module interface.
6. Electrical harness and equipment attachment.

2.1 BEAM-TO-BEAM CONFIGURATIONS

In the basic tetrahedral space structure, the beams are joined at the node points through the conical termination (closeout) structures and joint fittings. However, when two beams intersect at midspan or require joining in a parallel arrangement, special provisions must be made to join them. The principal design considerations for the attaching structures are their load transfer characteristics, ease of assembly, and transportability. The loads to which the joints are subjected are the axial loads along each of the principal axes of the beams and the moments about each of these axes.

A primary example of a structural configuration requiring attachments of crossing beams or "Tee" intersections is found in the tri-beam structure, a study concept being developed under Contract NAS9-15718 (Reference 1). The tri-beam concept is a 136 m long structure for the study of an engineering and technology verification platform having a self contained solar power array and a propulsion module for orbit transfer. One concept evaluated geodetic beams for the primary structural members and beam joining was a part of the structural studies. The overall structural concept (Figure 2-1) uses three parallel beams about 120 m long in a triangular arrangement with short transverse connecting beams. Figure 2-2 shows details of initial design concepts developed in Contract NAS9-15718 for joining the geodetic beams. Those concepts were expanded and developed in greater detail in Phase IA design studies of the Geodetic Beam program.

The basic approach generated in NAS9-15718 for beam attachments for geodetic beams used cradle or saddle type fittings with the beams connecting in an overlap configuration. The structural and packaging complexities of the cradle type fittings shown in Figure 2-2 are not established at this time since detailed designs of that concept have not been reported. The alternate approach explored by MDAC for the tri-beam platform involved end closure fittings for the short connecting beams intersecting the longitudinal beams along centerlines (Tee intersections) and attaching to elliptical stabilizing frames on the longitudinal beams. This arrangement minimizes induced bending in the beams caused by tensioning the cables that provide bracing in each bay of the tri-beam platform. The magnitude of such cable loads may increase if control force loads, propulsion loads, and dynamic responses resulting from such loads change significantly from early estimates. Also, the magnitude of dynamic response loads of the long relatively high aspect ratio structure may not be adequately predicted at this time. Thus Tee intersecting arrangements and crossing configurations of the connecting beams are shown in Figures 2-3 through 2-6.

The cradle attachment concepts shown in Figure 2-3 were studied to define concepts that have low weight and are easily transportable in the Orbiter.

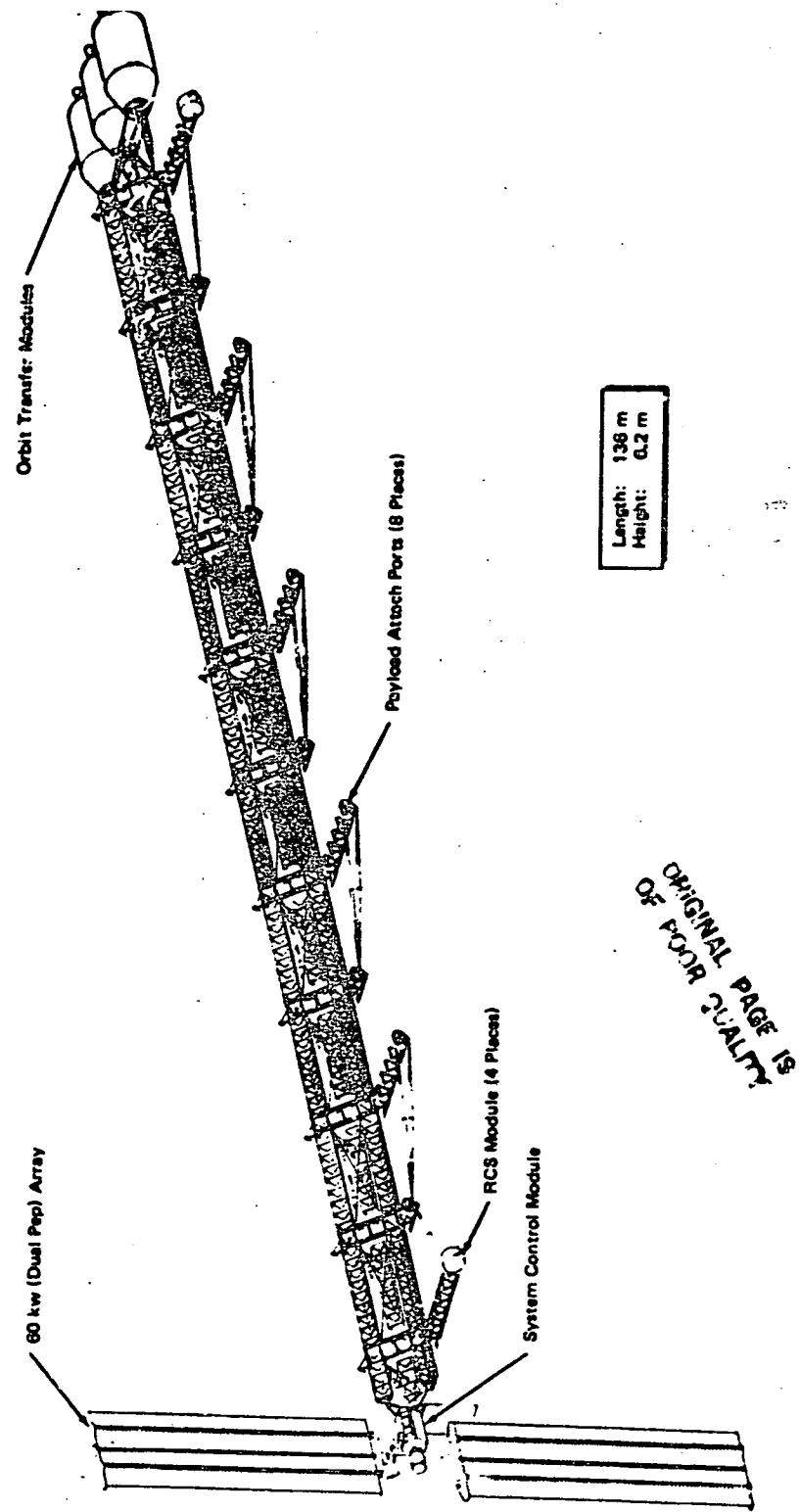


Figure 2-1. Tri-Beam Configuration

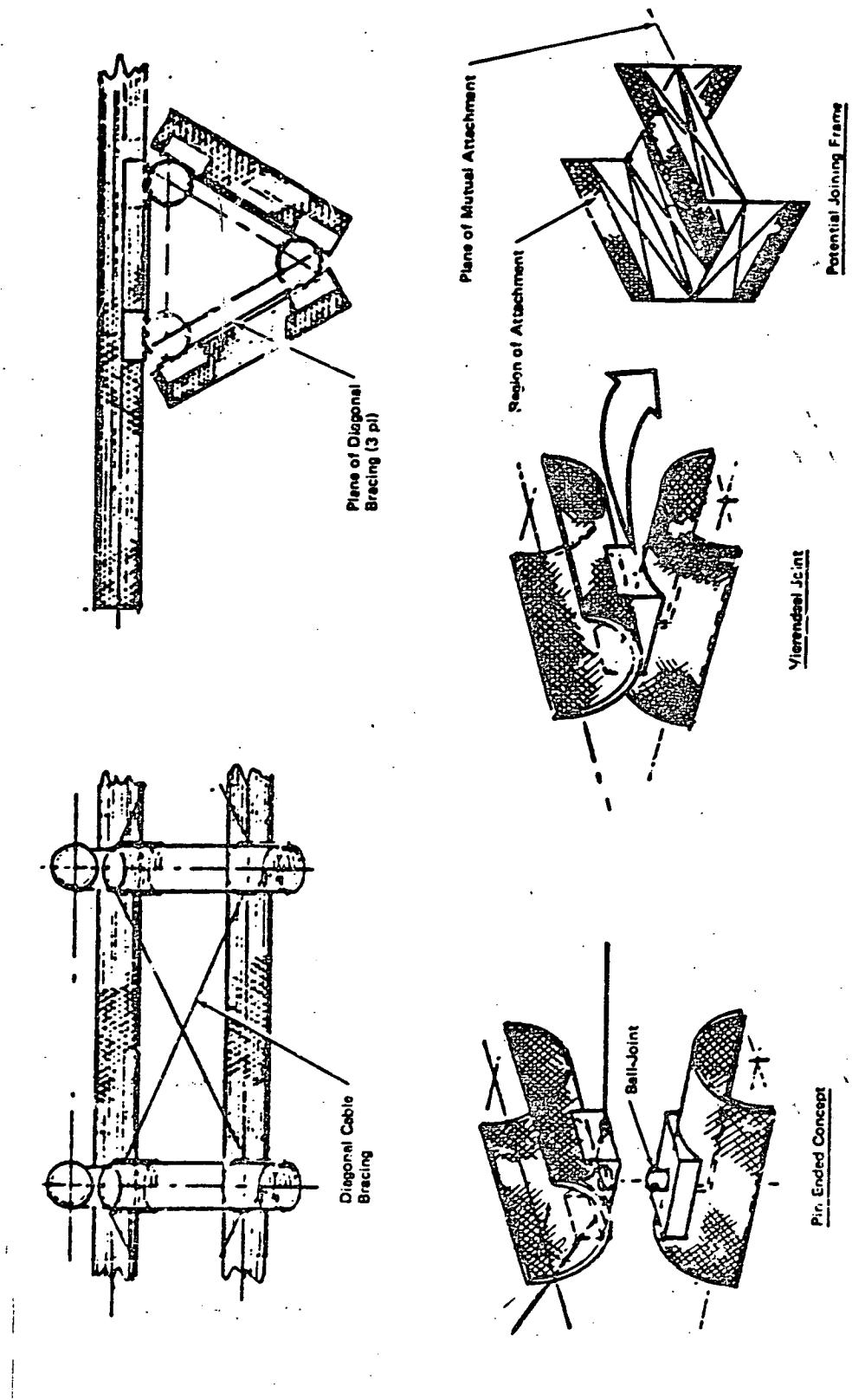


Figure 2-2. Initial Geodetic Beam Attachment Concepts .. Contract NASA-16719.

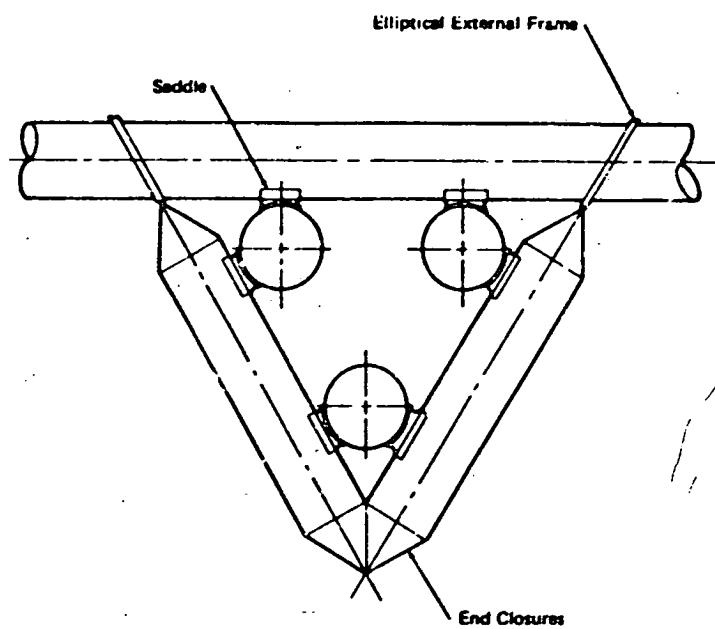


Figure 2-3. Payload Station Configuration – Internally Located Longitudinal Beams

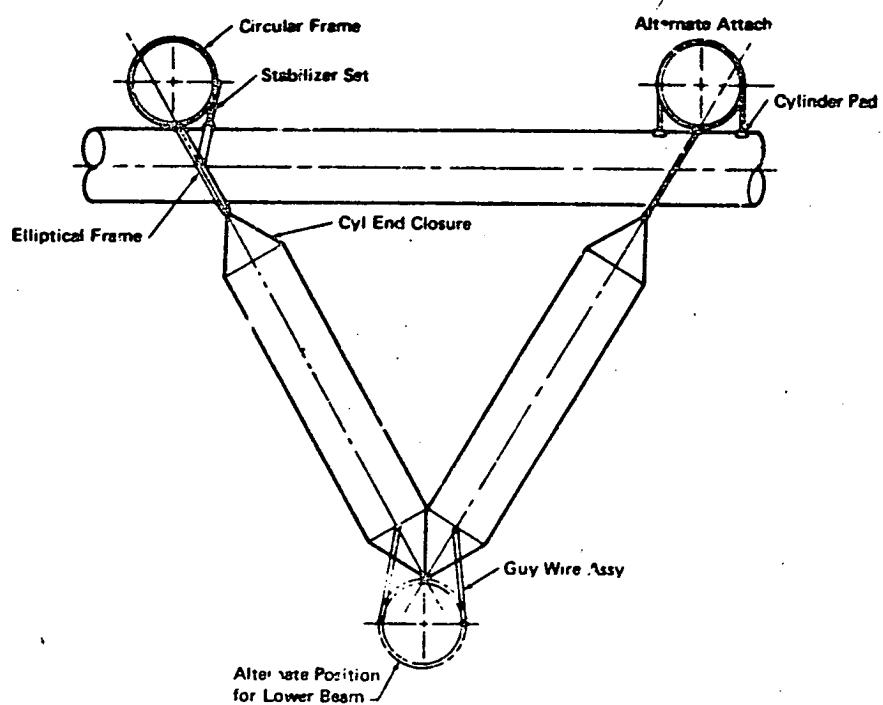


Figure 2-4. Payload Station Configuration – Externally Located Longitudinal Beams.

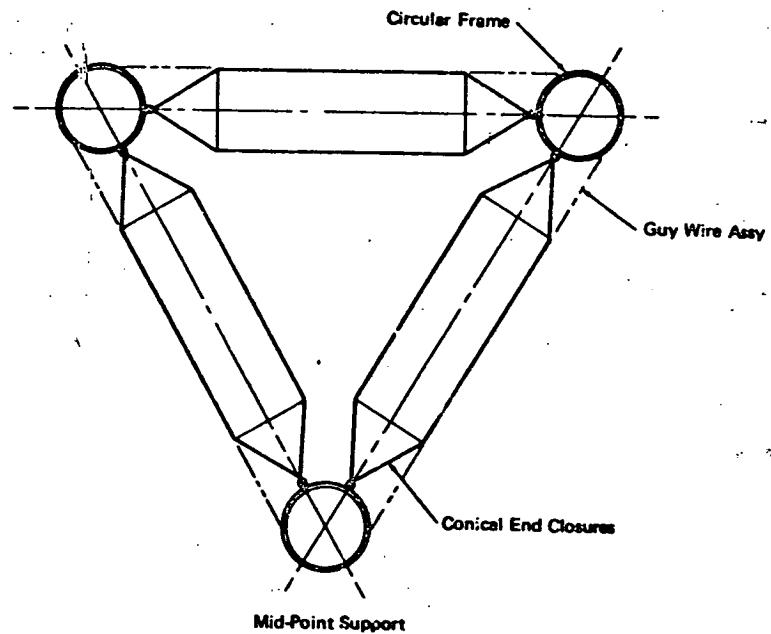


Figure 2-5. Cross Beam Arrangement at Intermediate Stations.

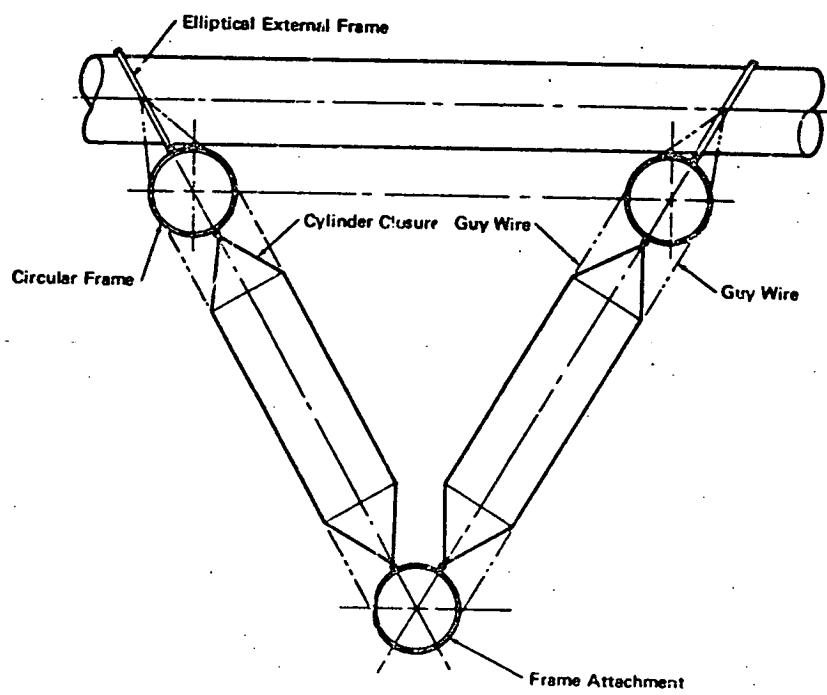


Figure 2-6. Cross Beam Arrangement at Payload Attach Stations.

Two variations of the cradle adapter are shown in Figures 2-7 and 2-8. In both types of adapter, the two crossing beams are each nested into the two faces of the cradle, and the adapter is attached to the beams through ring frames that are installed to distribute the loads to the longerons and helices in the geodetic beams.

The adapter is designed to fold flat for compact packaging and automatically latch into the operational configuration when unfolded. For ease of assembly, the adapter will be attached to the beam frames by means of expandable shear pins.

The frames and adapters are designed to be fabricated on earth and transferred aboard the Orbiter into orbit for assembly. To minimize packaging difficulties the frames will be made in 120° segments and assembled into a ring by means of quick release type clamps or fasteners at the three joints. The frames are designed to be positioned externally on an existing beam as Figures 2-3 through 2-6 indicate.

When the beams intersect at a predetermined angle, a relatively simple one-piece adapter, such as those discussed above, can be used. However, if more assembly flexibility is required, a two-piece adapter with adjustment features built into the interface can be designed. The logistics of providing the right adapter for each joint can be greatly simplified by using a reliable, lightweight, adjustable adapter.

Detailed layouts of the most promising concepts shown in Figures 2-3 through 2-8 were made to further evaluate details of frame attachments, cable attachments, folding concepts for beam interconnecting attachments, and methods of tensioning cables used in bracing large, open trusses. Figure 2-9 shows the use of folding/stowable interconnecting frames that join crossing beams or beams that are closely spaced in a parallel arrangement. A single point attachment, an adjustable fitting providing variable beam crossing angle, and modified cradle type fittings that attach to external frames on the geodetic beams were studied as shown in Figure 2-9. Cradle interconnect details and

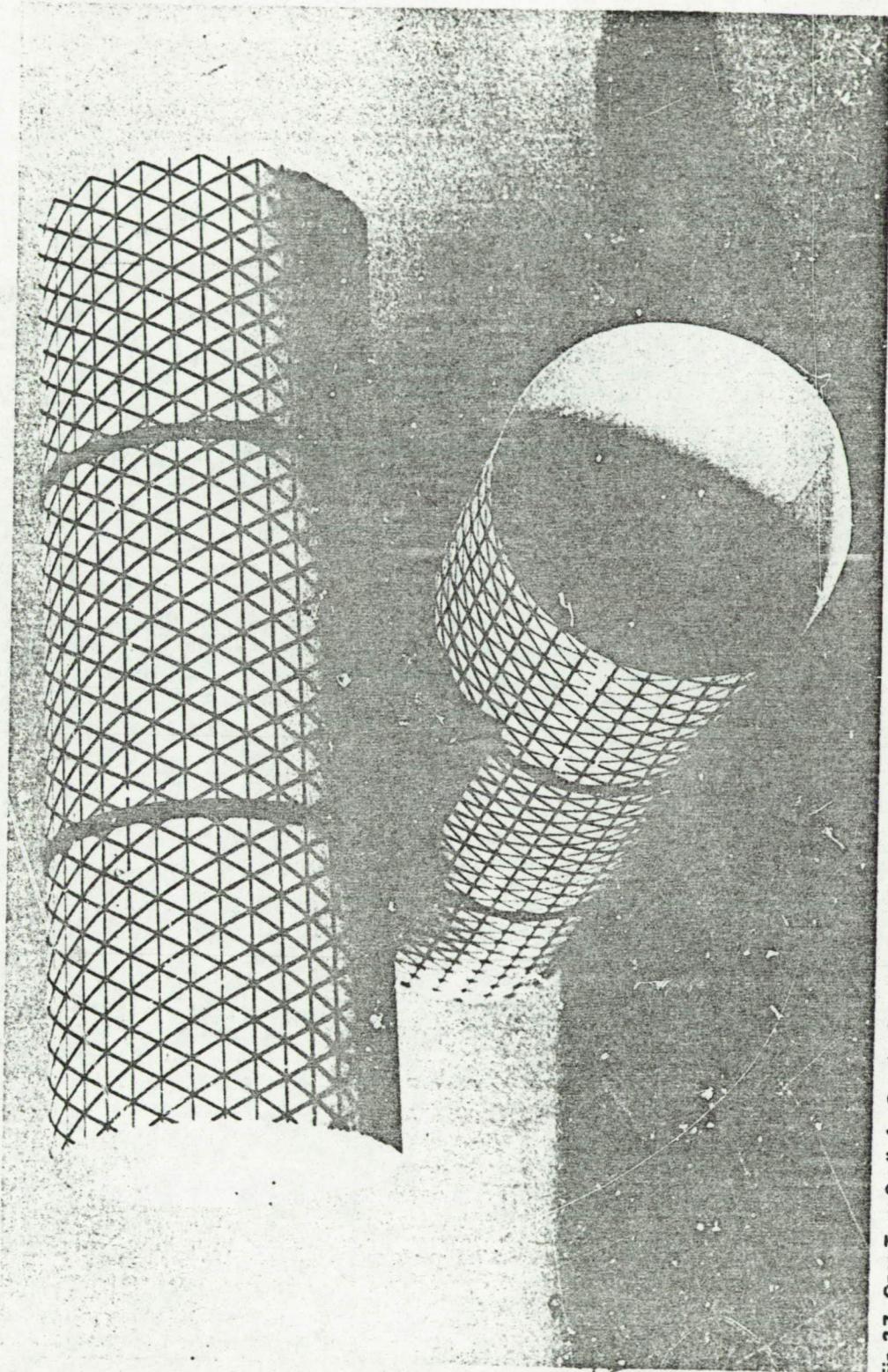
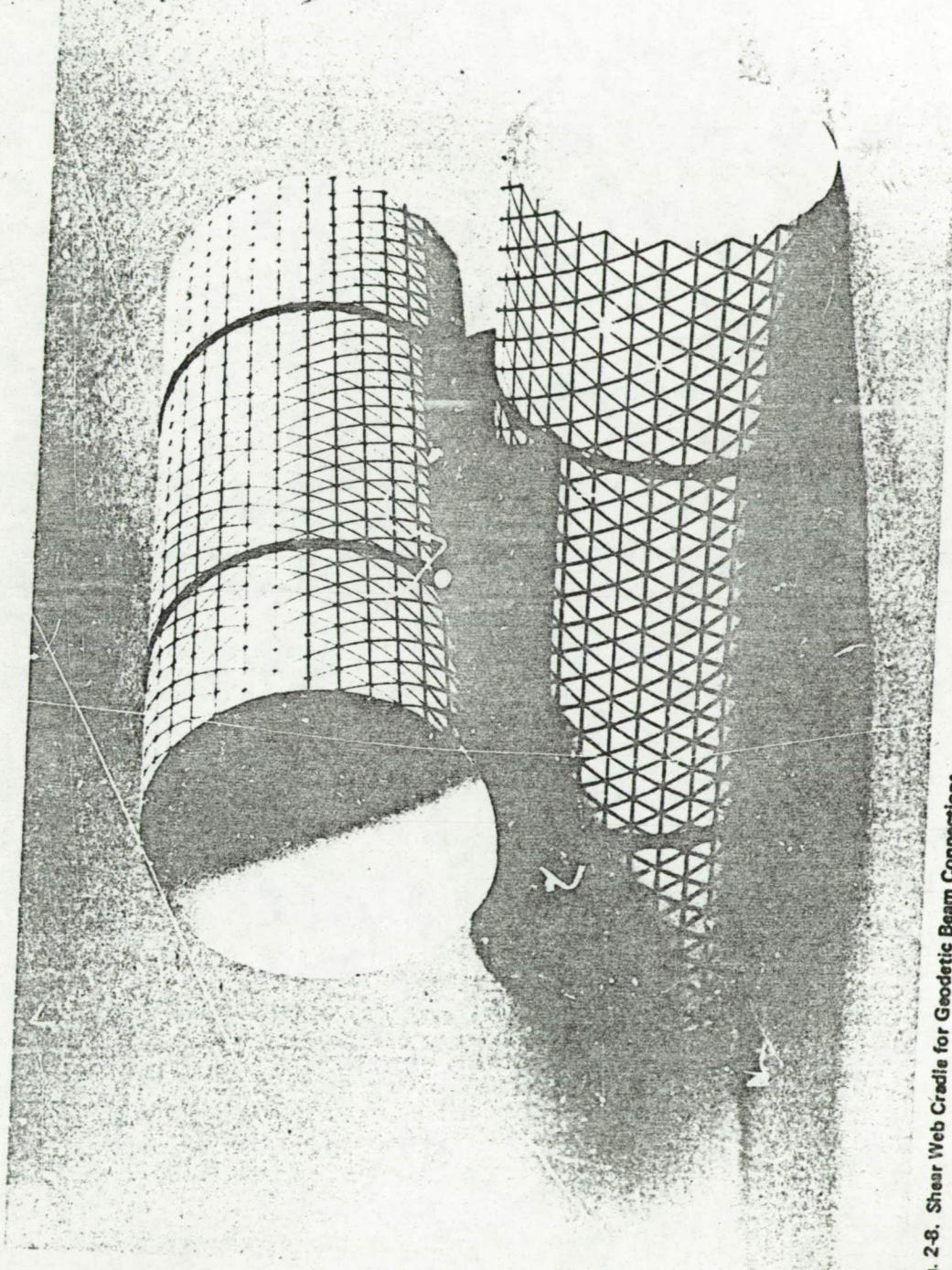
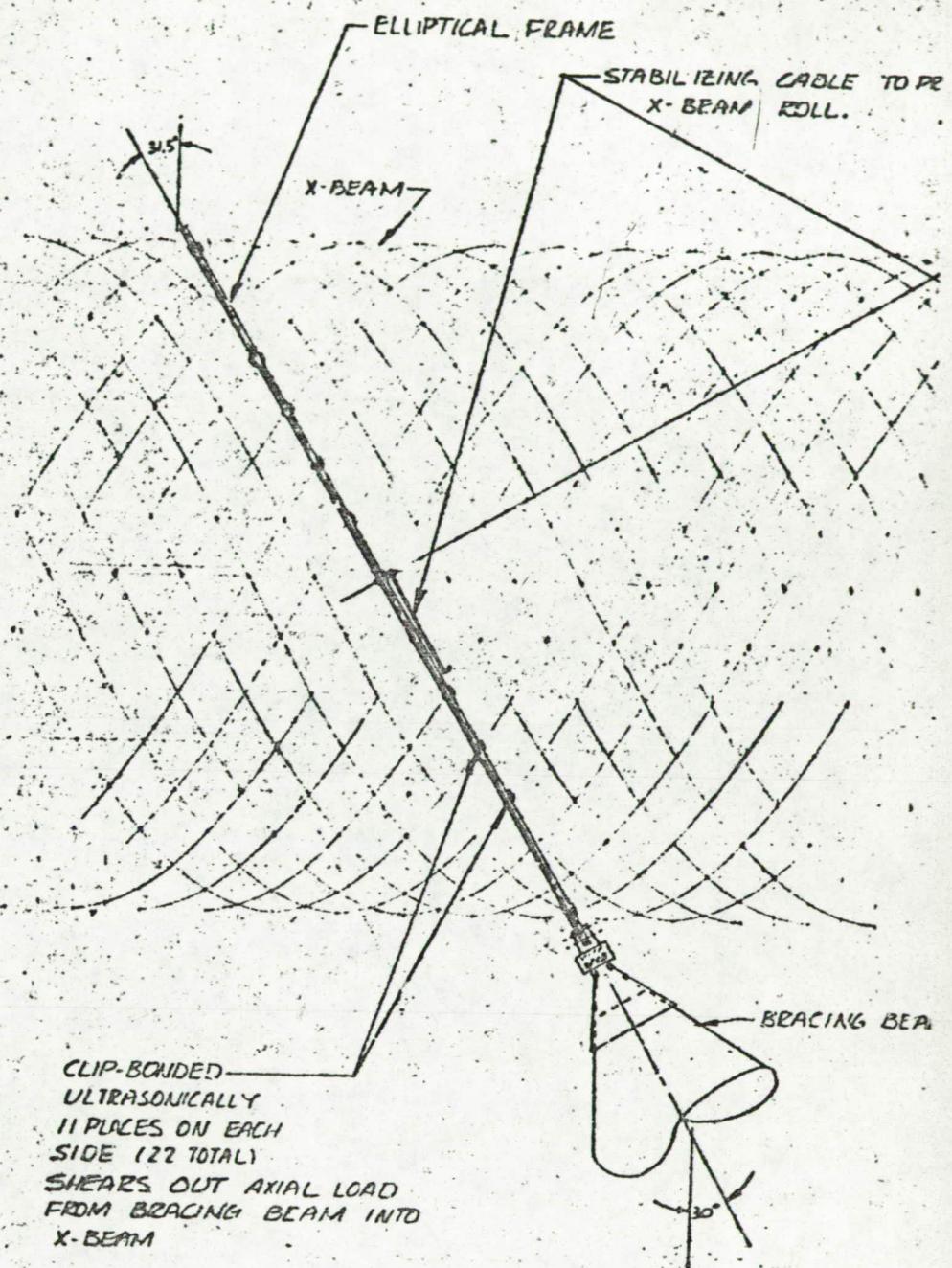


Fig. 2-7. Open Truss Cradle for Crossing Beam Attachment



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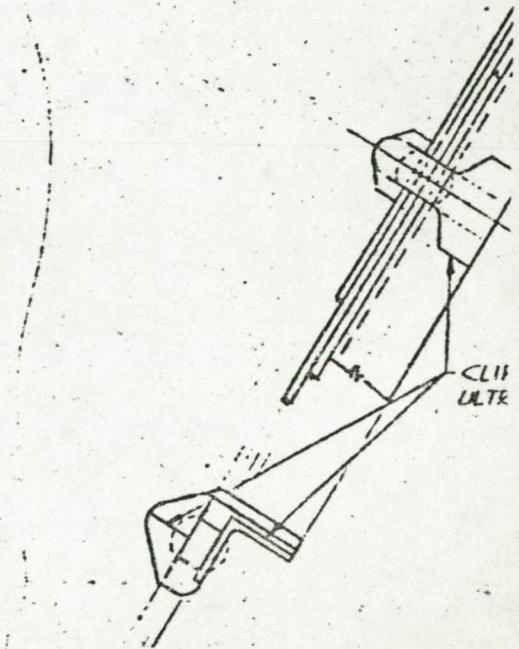
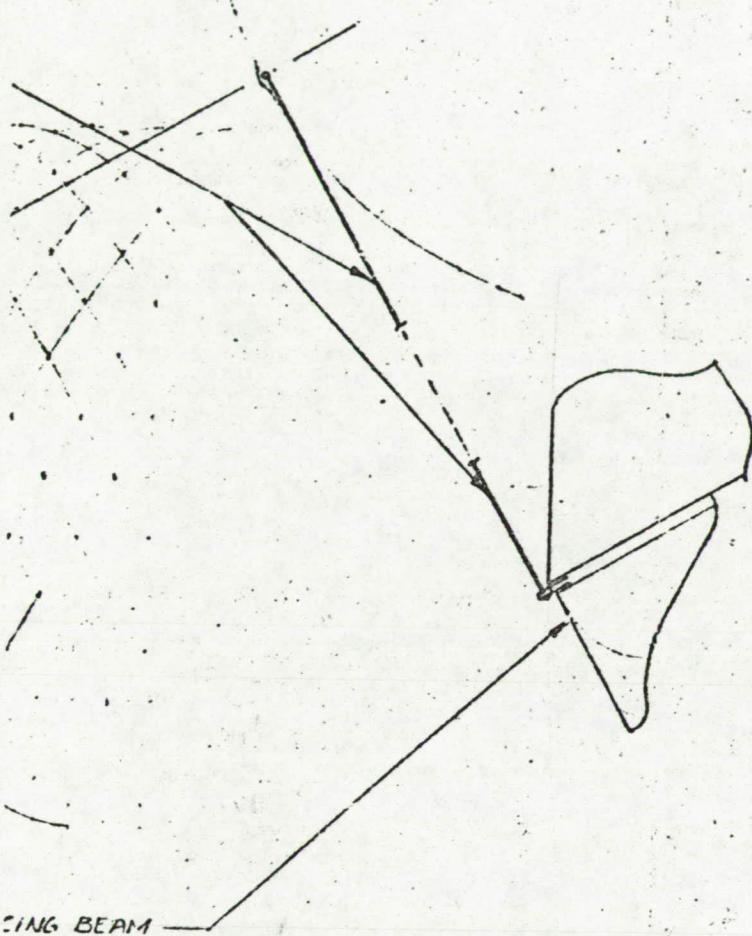
Fig. 2-8. Shear Web Cradle for Geodetic Beam Connections



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LE TO PREVENT
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FOLDOUT FRAME 2

1. 90° INTERSECTION - COULD BE MODIFIED TO FOR OTHERS.

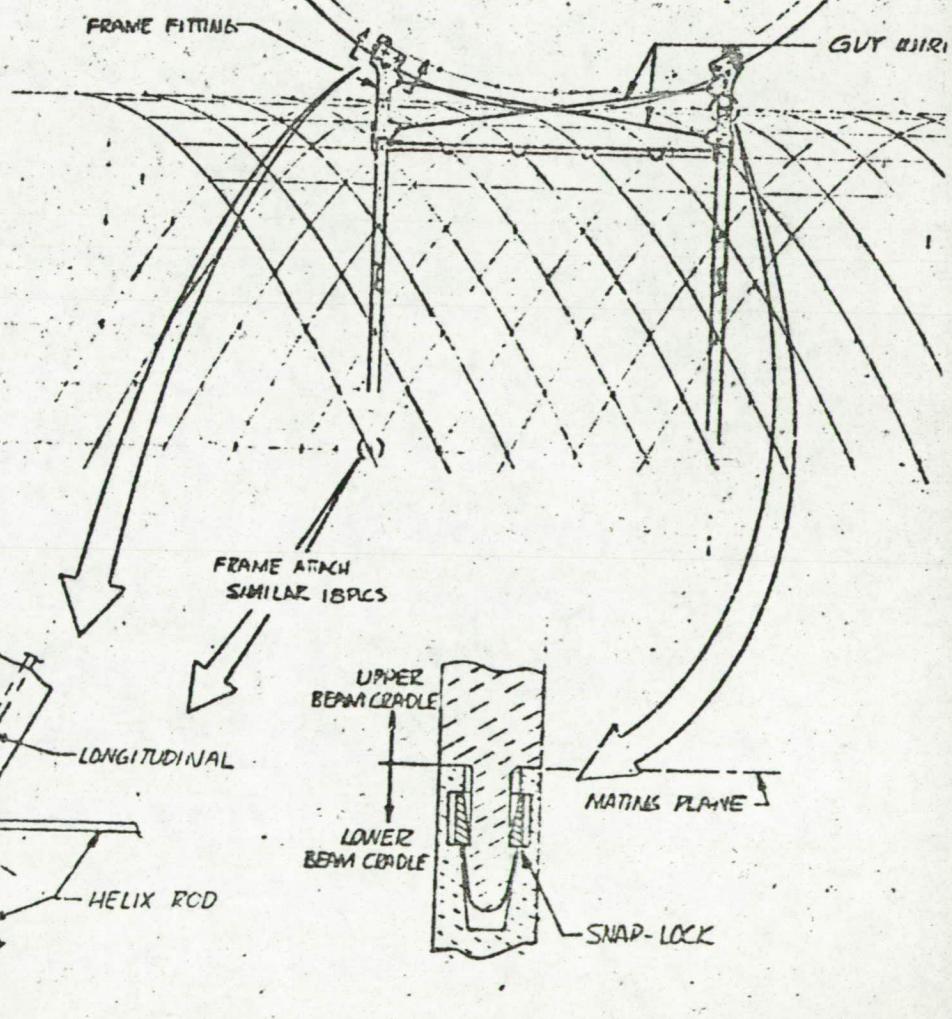
2. FOUR (4) RIGHT & FOUR (4) LEFT HAND FRAME FITTINGS. JOIN TOGETHER AT MATING PLANE.

3. TWO (2) IDENTICAL FRAME SETS FOR EACH BEAM

- 3 120° SECTIONS
- 3 FRAME SPLICES
- 18 FRAME TO ROD ATTACHMENTS.

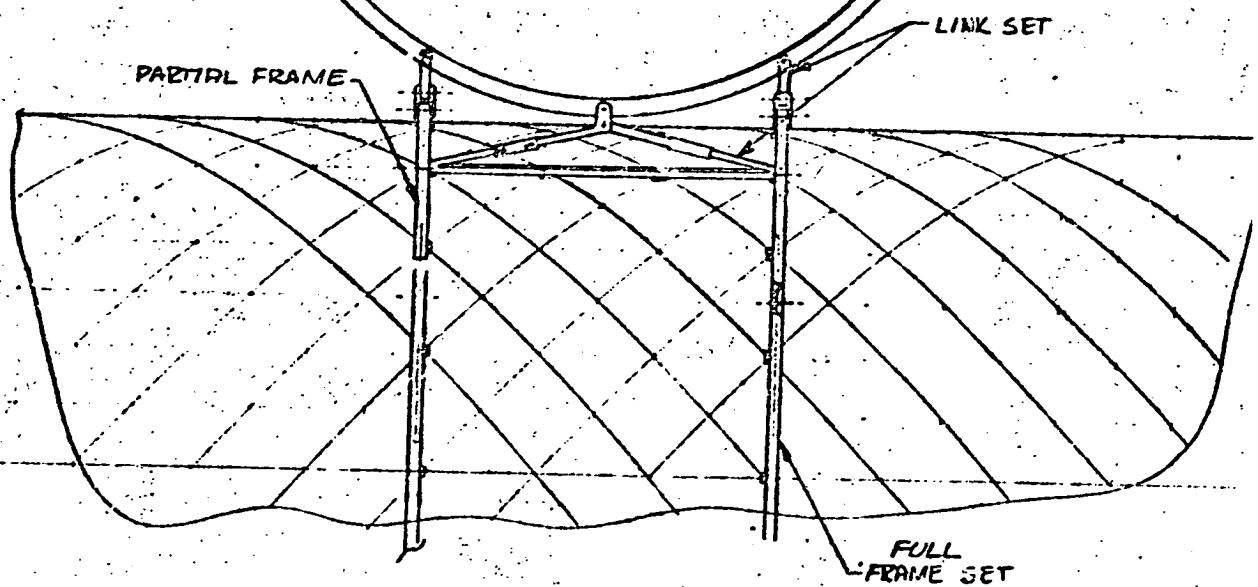
4. AFTER 4 POINT MATE INSTALL AND TIGHTEN GUY WIRES.

5. MODERATE TO HEAVY LOAD AND MOMENT CAPABILITY IN ALL 3 AXES.



FOLDOUT FRAME

- 1. 90° INTERSECTION - COULD BE MODIFIED TO HANDLE 10-20° DEVIATIONS.
- 2. FOUR (4) IDENTICAL LINK SETS.
 - 3 ATTACH POINTS EACH (12 TOT)
 - 2 ADJUST PTS (8 TOT)
 - STACK FLAT FOR TRANSPORT
- 3. TWO (2) IDENTICAL FRAME SETS
 - 3 120° SECTIONS
 - 3 FRAME SPLICE ATTACHMENTS
 - 18 FRAME TO KOD ATTACHMENTS
- 4. MODERATE LOAD AND MOMENT CARRYING CAPABILITY.
- 5. COULD ACCOMMODATE PARTIAL FRAME.



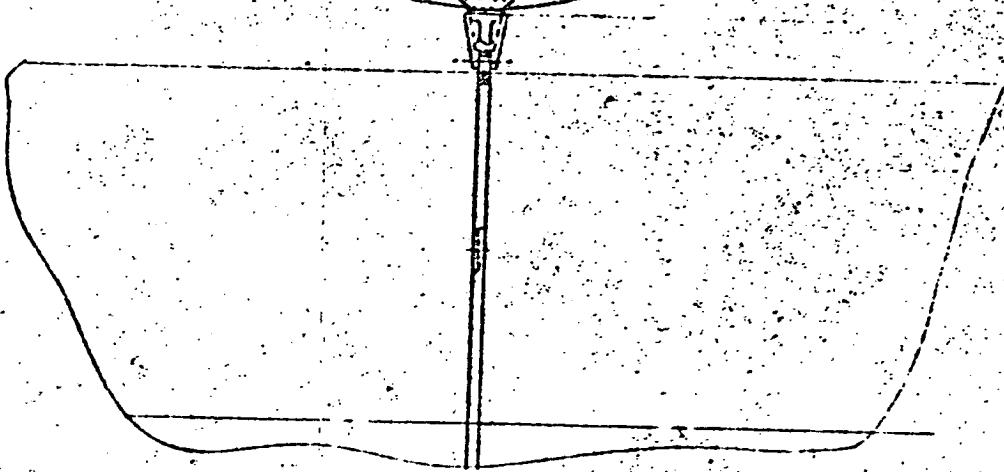
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4

SINGLE POINT ATTACH

1. NO ADJUSTABILITY ALONG AXIS OF EITHER BEAM.
2. MODERATE TO LOW LOAD CARRYABILITY.
3. RELIES ON FRAME STIFFNESS TO TRANSFER LOAD INTO BEAM.



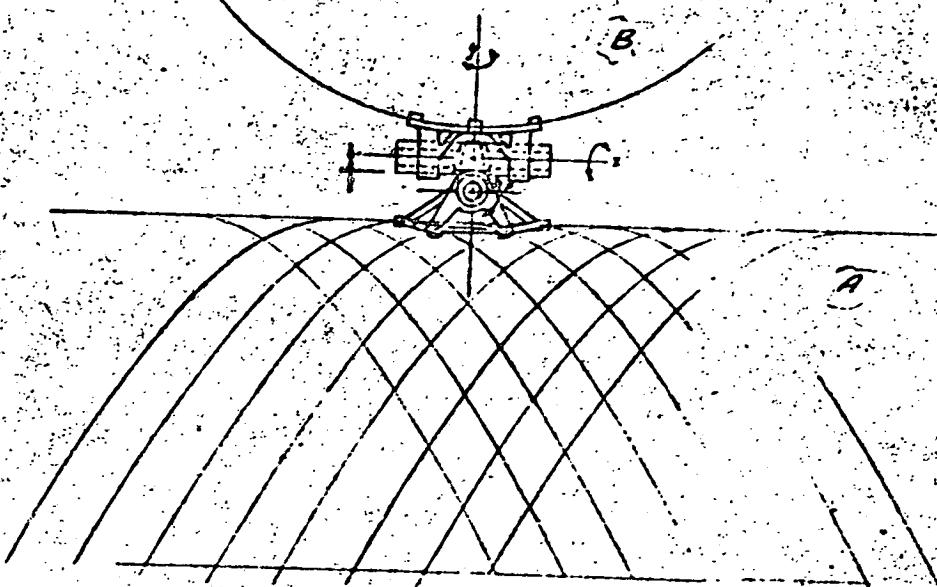
FOLDOCUT FRAME S

ADJUSTABLE MATCH.

1. COME FROM G.B.A. MATES TO REC. IN G.B.B. AND CLOSES CIRCUIT WHILE SEATED. (ON Y-AXIS)
2. 3-AXIS ROTATION (ABOUT X Y Z), AND TRANSLATION (IN X & Z) CAN BE ADJUSTED.
3. JOINT IS LOCKED MECHANICALLY. THE ORD. PINS AND THE ADHESIVES.

ADJUSTMENTS $X = 25^\circ, \pm 2.0 \text{ m.s.}$
 $Y = 60^\circ$

2. MODERATE LOAD CAPACITY:



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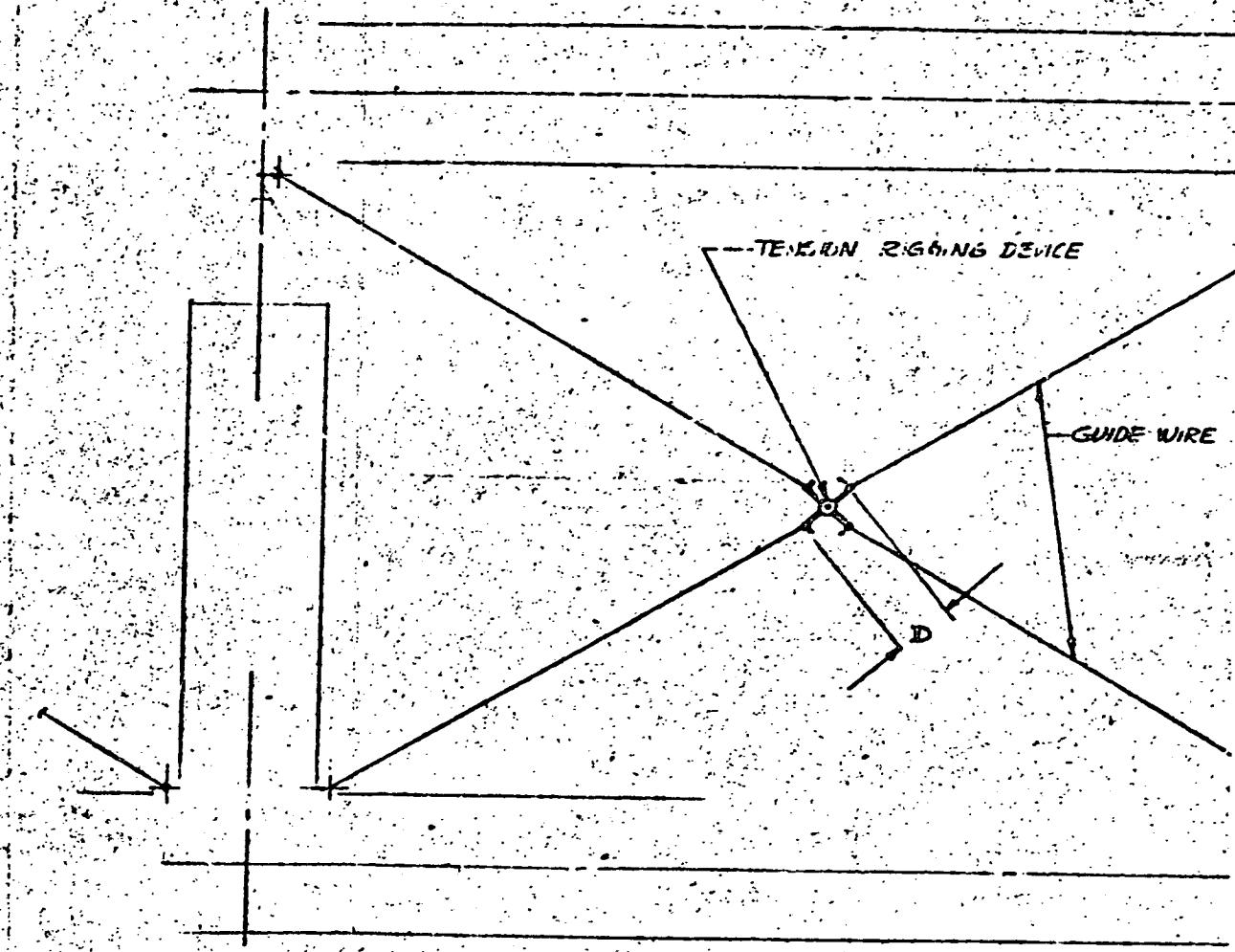
Figure 2-9. Beam-to-Beam Attachments.

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frame attach details at node positions are also shown in Figure 2-9. Elliptical external frames were also investigated for use in connecting beams at angles other than 90°. Layouts for the elliptical frames showed that a majority of the longitudinal-helix node positions can be used for attaching the frame. The detailed layout (Figure 2-9) used a 36-longitudinal arrangement, and 30 longitudinal-helix node positions can be used for attachment points with an elliptical frame with a 30° cant from a position normal to the beam centerline. The spiral pattern of the helices prevents use of all 36 node positions; however, load transfer was considered satisfactory using 30 (>80%) of the nodes.

Figure 2-10 shows additional geodetic beam-to-beam attachment concepts. An alternate configuration for a tri-beam type of structure is shown in Figure 2-10, as well as a platform made from widely spaced geodetic beams in a parallel arrangement. Attachment of thrust structures, saddle type fittings for beam-to-beam attachments, cable attachment details, and cable tensioning fittings are shown in Figure 2-10.

The studies of geodetic beam attachments conducted during Phase IA show that various connecting designs are viable for use in structural arrangements requiring crossing beams, beams that intersect at various angles, parallel beams, and beams requiring cable attachments. Also, fitting attachments for introducing high thrust loads and external frames for introducing beam connecting loads were investigated. The design work conducted in this task shows the versatility of the geodetic beam for use in a number of structural arrangements that may be required for various large space systems.



VIEW 2 SCALE 1/2

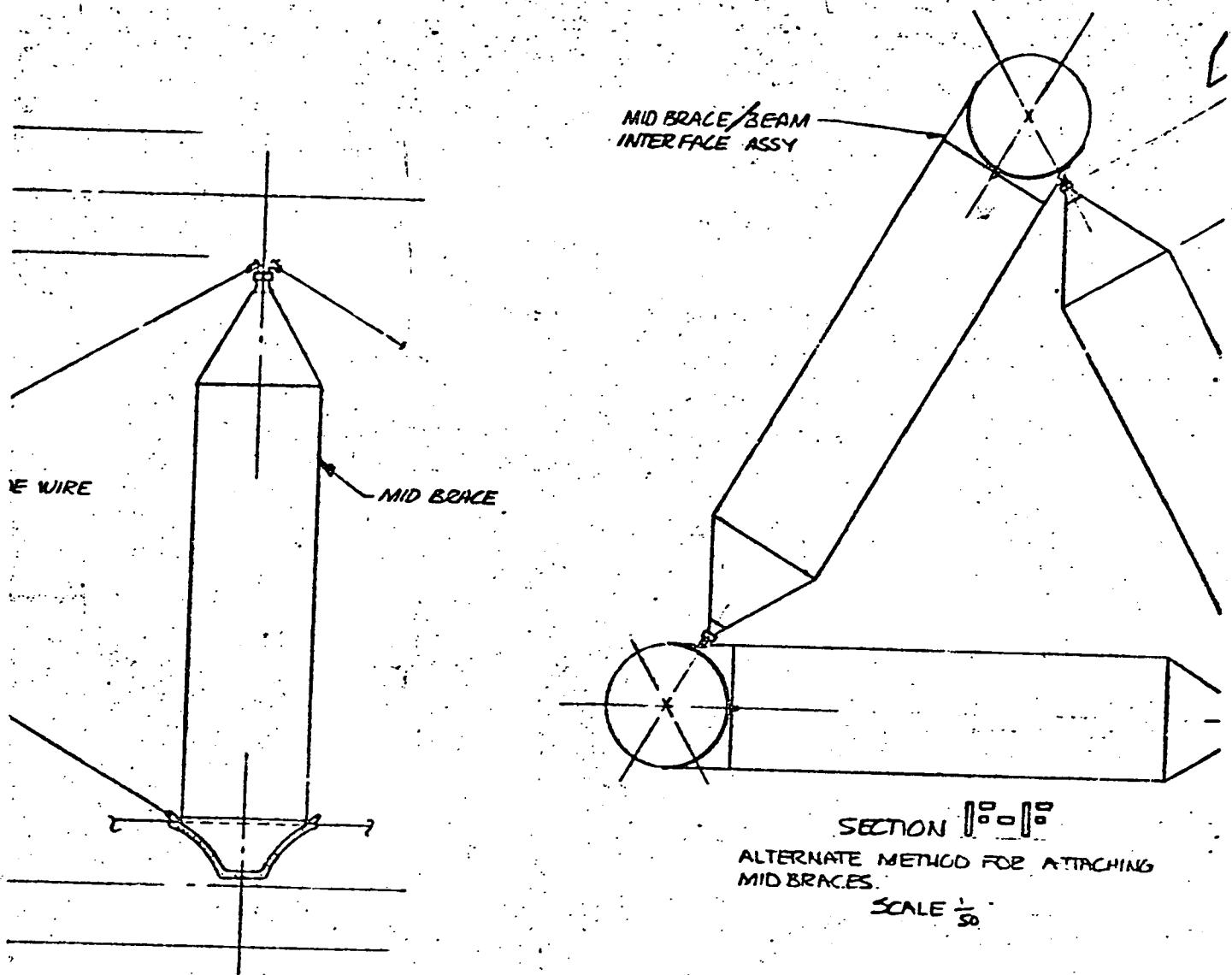
THE TENSION RIGGING DEVICE (TRD) ESTABLISHES AN EQUAL PRELOAD IN THE WORKING ONE WIRE AGAINST THE OTHER. SINCE THE TRD IS NOT RE- SYSTEM ACHIEVES EQUILIBRIUM WHICH IN TURN RESULTS IN THE FOR IN THE WIRES AND SHEAR AT THE BAR LINK/GUIDE WIRE INTERFACE) BE- OPPOSITE.

THE DIAMETER 'D' OF THE TRD WILL BE DEVELOPED TO ACCOUNT FOR T SLACK RESULTING FROM:

1. MANUFACTURING TOLERANCES OF GUIDE WIRES,
2. MANUFACTURING TOLERANCES OF MID BRACES,
3. POSITIONING ACCURACY OF THE MID BRACE SECTIONS
4. PRELOAD REQUIRED (I.E. HIGHER PRELOADS RESULT IN MORE STRETCHING OF THE WIRE WHICH WILL REQUIRE BETTER MECHANICAL ADVANTAGE)
5. ASTRONAUT TORQUE INPUT CAPABILITIES,
6. RIGGING PROCEDURES.

EQUIPMENT ELEMENT

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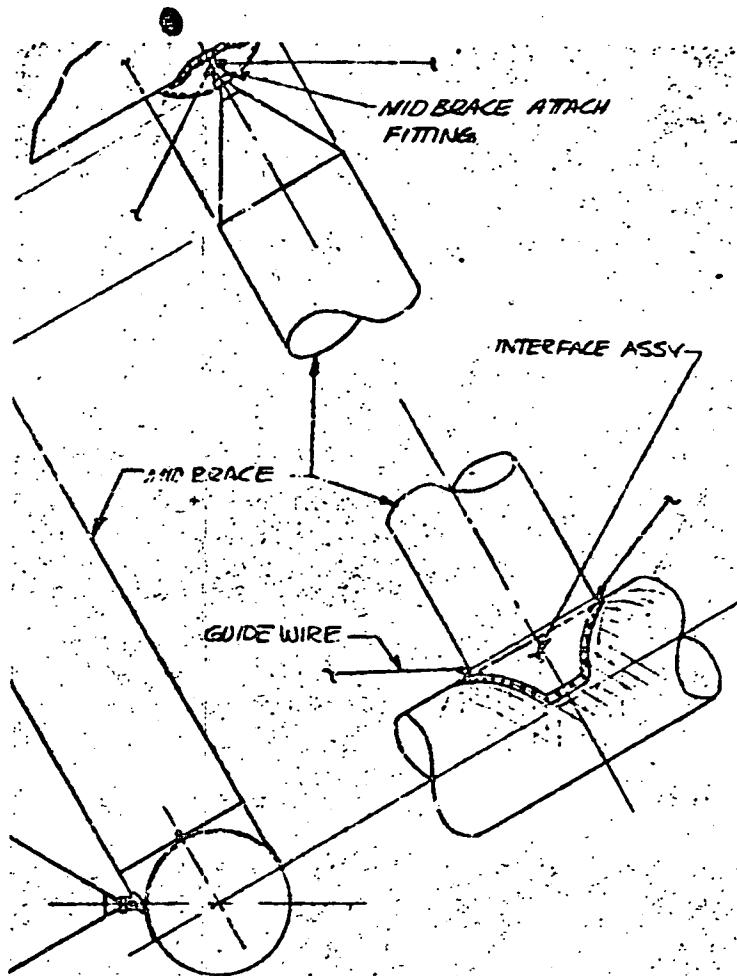
D IN THE GUIDEWIRES
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THE FORCES (TENSION
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F FOR THE SYSTEM

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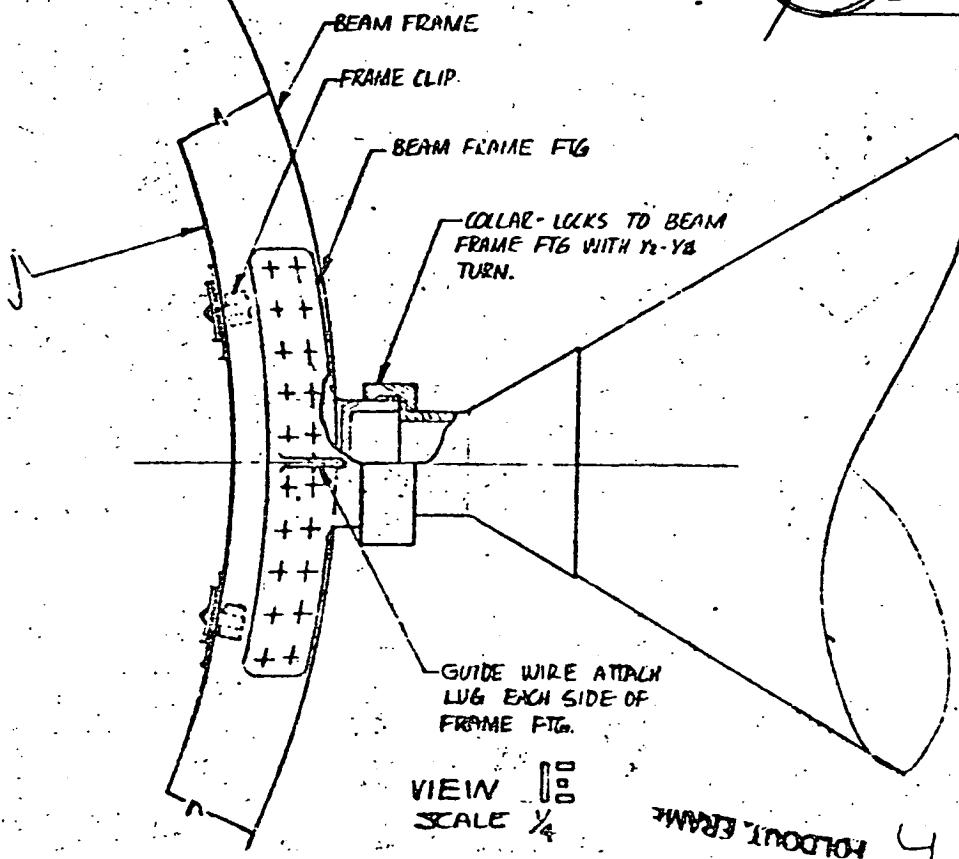
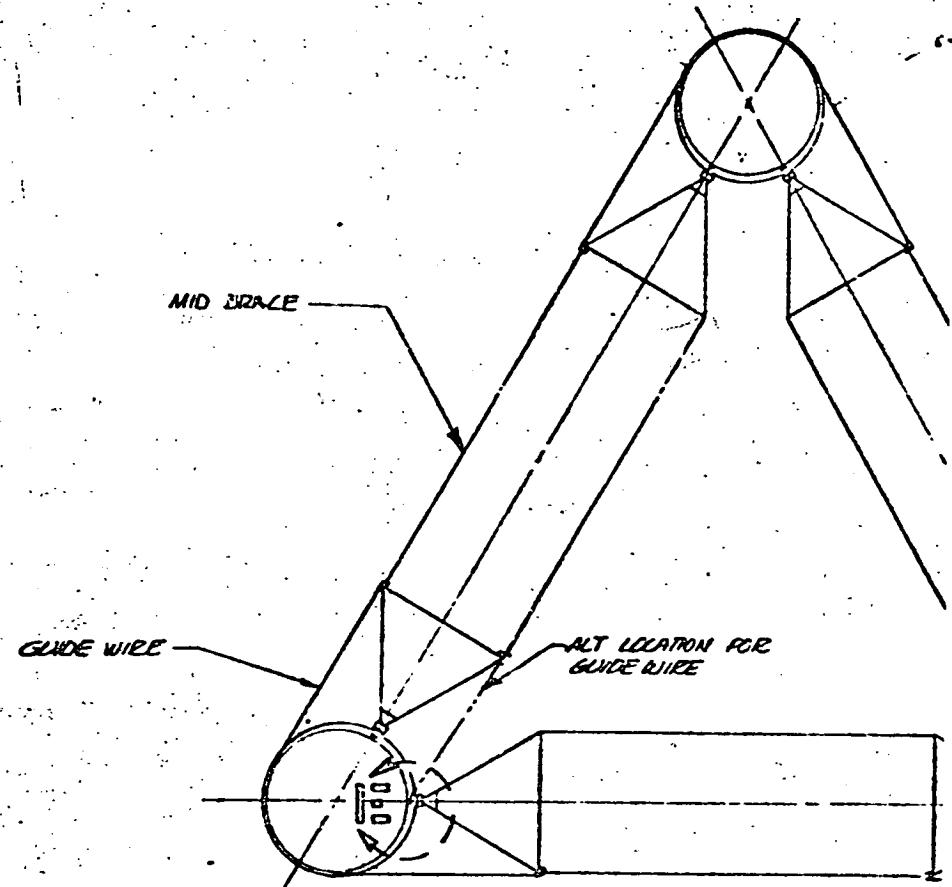
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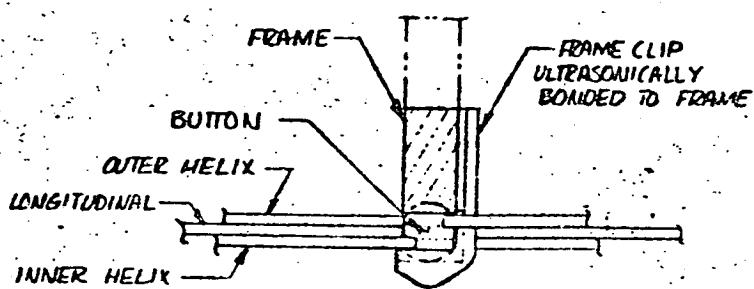
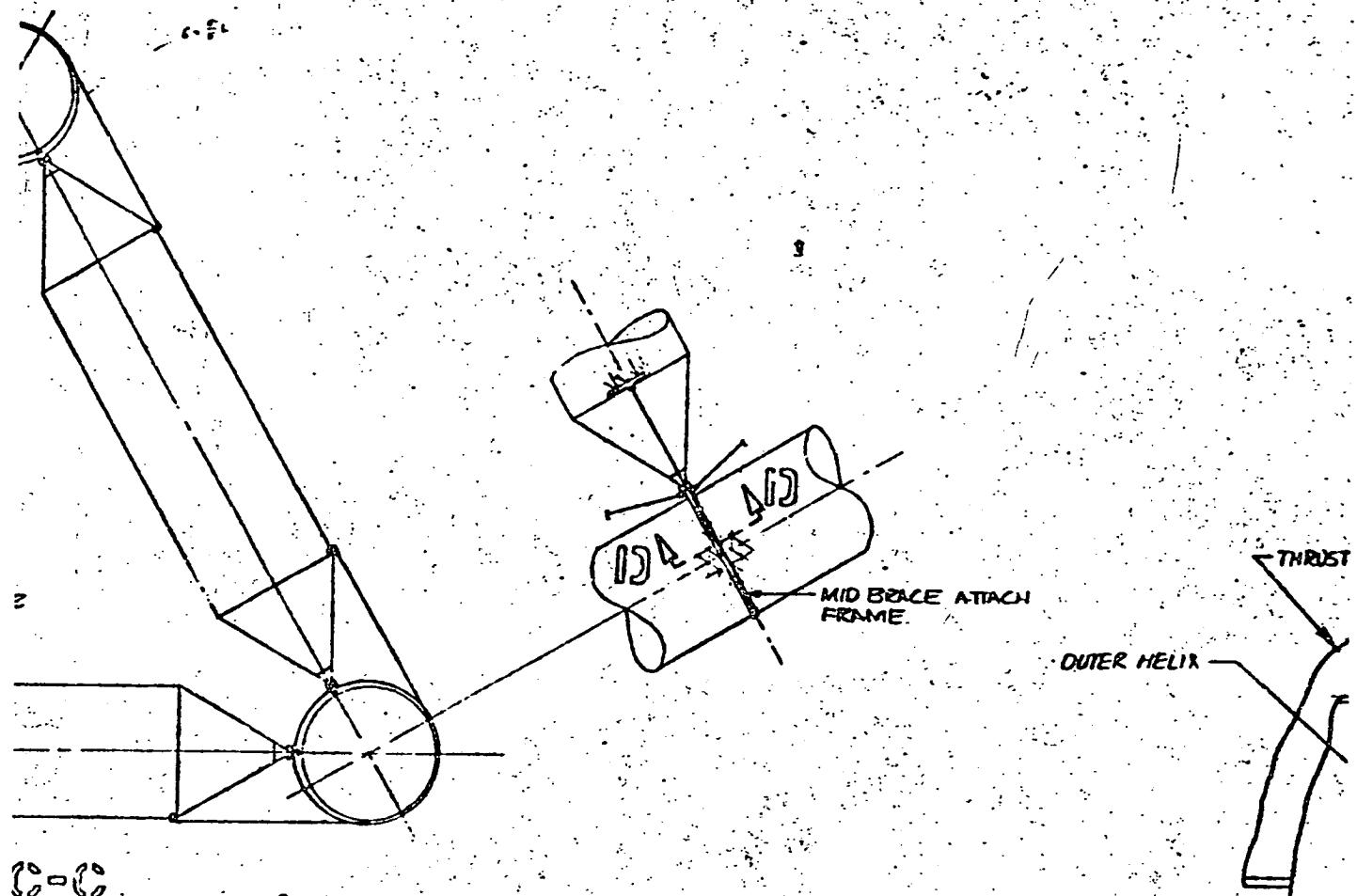


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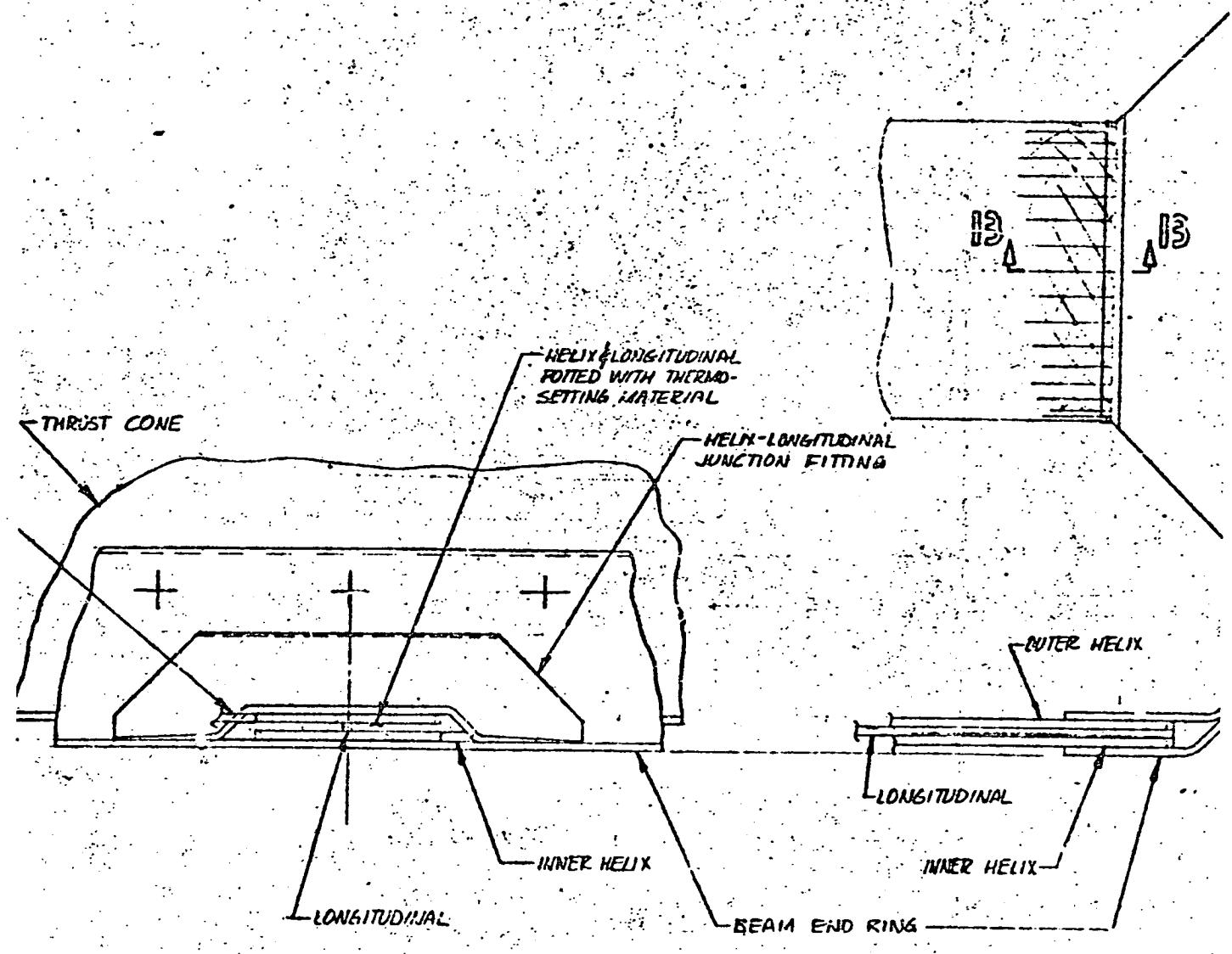




SECTION 10-10
ATTACHMENT TO FRAME TYPICAL
18 PLACES AT EACH FRAME.

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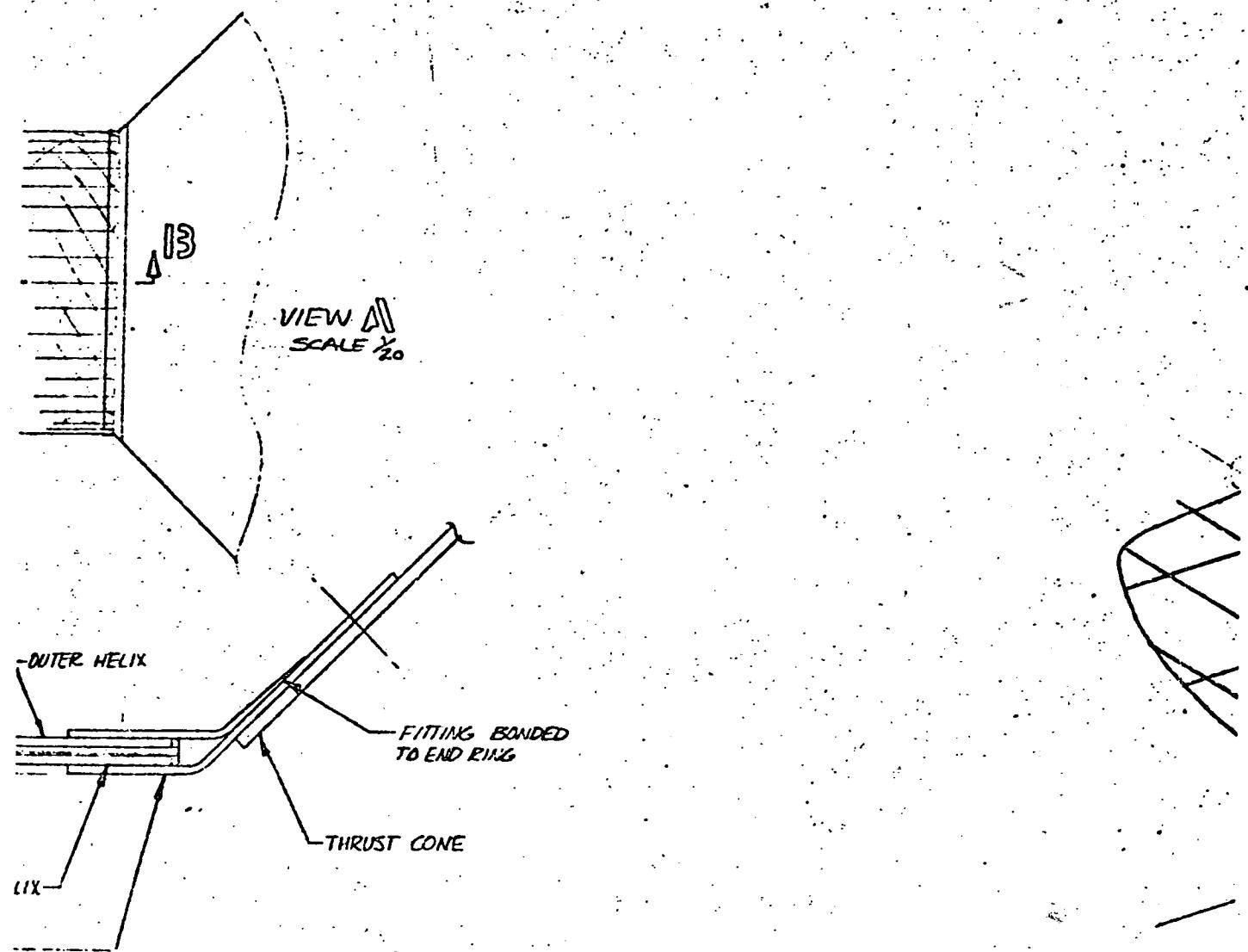
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SECTION 13-13
SCALE 1/4

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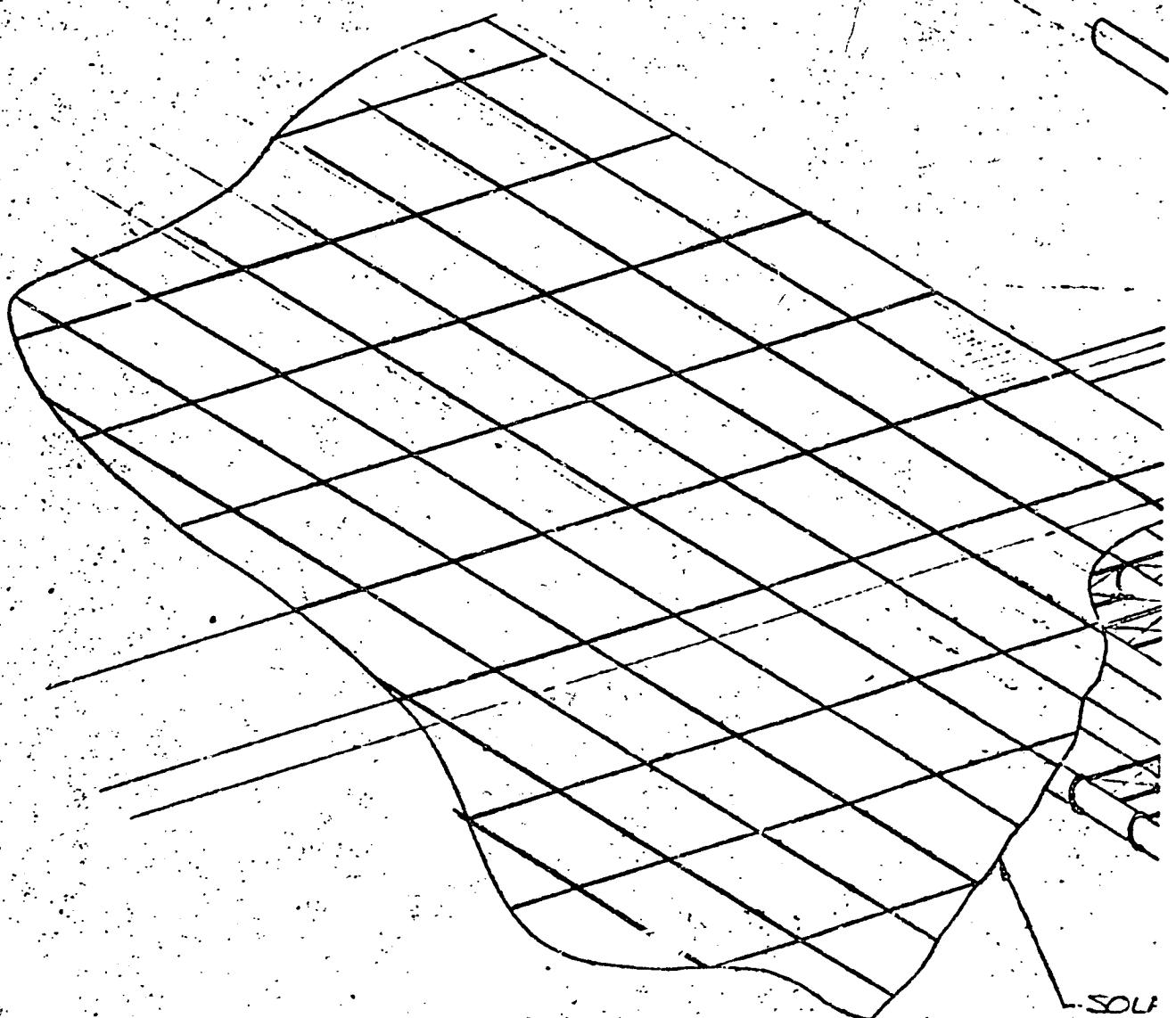
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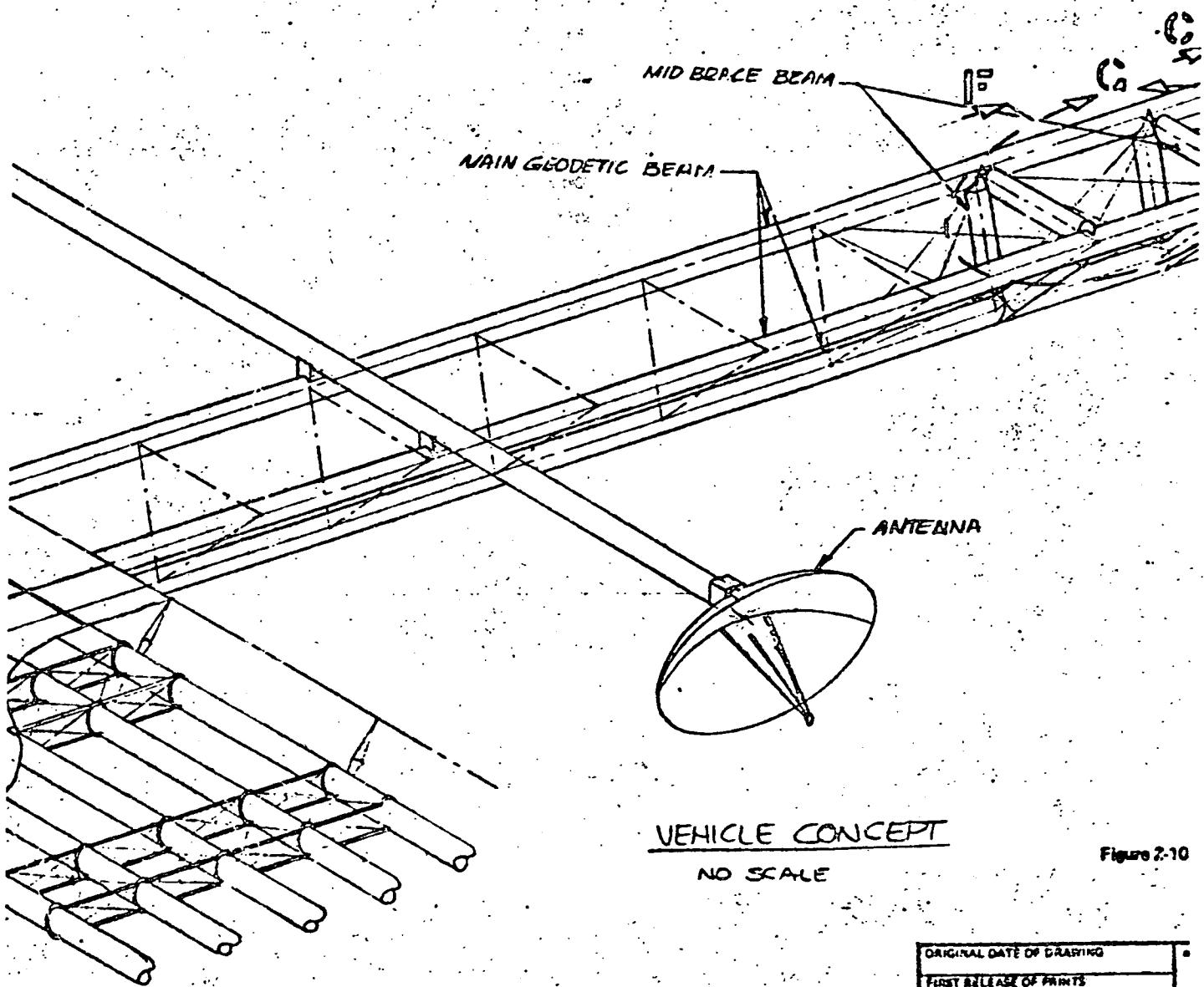


Figure 2-10

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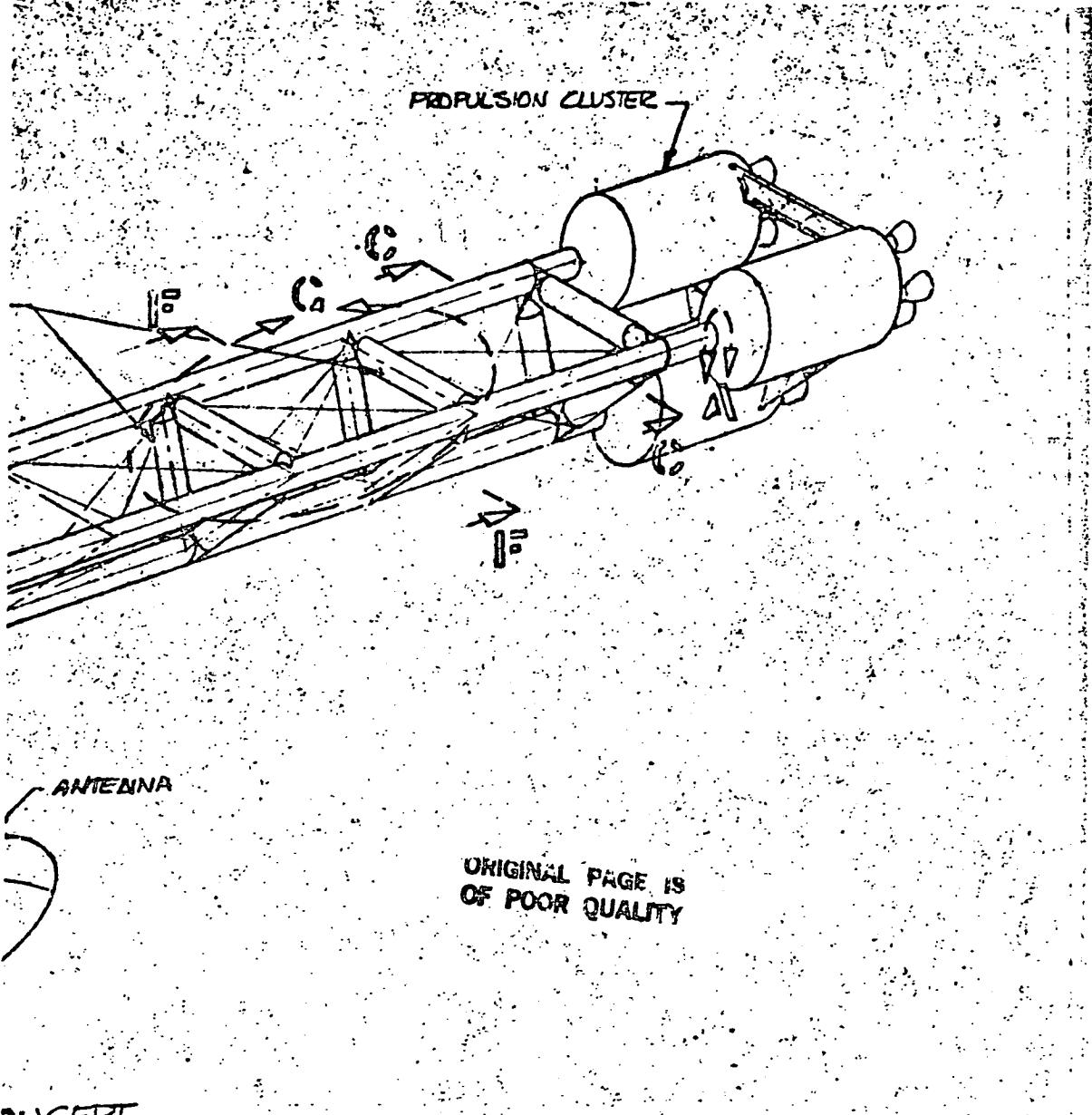


Figure 2-10. Geodetic Beam Attachment Concepts

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PRODUCTION			McDONNELL DOUGLAS	
NSP			McDONNELL DOUGLAS	
MECHANICAL			SIZE	CODE IDENT NO.
PROPELLION			18355	DRAWING NO.
STRUCTURES			SK-JFD 800124	
	SCALE	CONTR NO.	SHEET	OF

BEAM ARRANGEMENT
CONCEPTS - GEODETIC
BEAM

Section 3 LONG LIFE MATERIAL

Phase I studies (Reference 2) of design requirements for structural truss members in large space structures, e.g., the solar power satellite (SPS), showed the maximum temperatures for some elements to be approximately 235°C (455°F). This requirement was limited to certain portions of micro-wave power transmission antennas and is caused by heat rejected from micro-wave transmitting units. To meet this limited requirement, a portion of Phase IA was devoted to establishing feasibility of pultruding rod stock with a resin system capable of service up to 235°C (455°F). A survey of potential resins showed that the du Pont NR150A2 series of resins offered a good probability of success in pultrusion operations, and their maximum service temperature is approximately 260°C (500°F). Also, evaluations of coatings capable of reducing temperatures were conducted to determine their compatibility with the NR150A2 resin system used in the pultrusion trials.

3.1 HIGH TEMPERATURE PULTRUDED ROD MATERIAL

Experimental quantities of two variations in the NR150A2 series of du Pont resins were procured for use with HMS fibers in making prepreg materials. The NR150A2 type resin was chosen because of its high temperature service capabilities and its thermoplastic-type behavior which permits joining by heat fusion techniques if required.

The two variations of HMS/NR150A2 that were obtained for pultrusion testing were HMS/NR150A2-S5X and HMS/NR150A2-060X. These resin systems are special formulations of polyimides that were suggested by the manufacturer (du Pont) as being suitable for pultrusion. During the actual trials, the HMS/NR150A2-S5X was dropped due to the high volatile content of the prepreg tape. Tests of the prepreg material showed the -S5X prepreg to have 12.0% volatiles in one sample and 16.9% in a second sample. The desired volatile content for achieving successful pultrusion of the tape is <5%. The HMS/NR150A2-060X material met this criterion, having a volatile content of 4.5%. The resin content and

percent volatiles for the two types of prepreg tape were as follows:

<u>Material</u>	<u>Wt. Percent of Resin</u>	<u>Wt. Percent Volatiles</u>
Sample 1 HMS/NR150A2-S5X	34.6	12.0
Sample 2 HMS/NR150A2-S5X	32.3	16.9
Sample 3 HMS/NR150A2-060X	29.3	4.9

Approximately 80 linear feet of circular cross-section rod made from HMS/NR150A2-060X polyimide was pultruded with a 2.36 mm (0.093 in) diameter by Compositek Engineering Corporation (CEC) in two runs. As shown in Figure 3-1, the bushing/die assembly consisted of five oversize circular bushings upstream from the 2.36 mm diameter die. The die itself is shown in closeup in Figure 3-2. In both photographs the pulling direction is from left to right. Pulling speed was 3.8 cm per minute (1.5 in/min) and temperature of bushings and die was 427°C (800°F). The five bushings, arranged with progressively smaller apertures, had diameters of 5.08 mm (0.200 in), 3.175 mm (0.125 in), 2.870 mm (0.113 in), 2.489 mm (0.098 in), and 2.362 mm (0.093 in.).

After completion of pultrusion, a check was made on the degree of cure of the pultruded material because the relatively short time at high temperature in the bushing/die system was judged insufficient for complete cure. In accordance with conversations with du Pont representatives, samples were weighed, then placed in an oven and post cured two hours at 315°C (600°F). These specimens were cooled in a dessicator and reweighed. About 0.4% weight loss occurred, indicating incomplete cure. According to du Pont this weight loss should not have exceeded 0.2% if the material had been fully cured. Therefore, to complete the cure, all HMS/NR150A2-060X pultruded rod material was processed as follows per du Pont recommendation:

1. Material was placed in forced air circulating oven at room temperature.
2. Heat to 315°C (600°F) in about a 2-1/2 hour period.
3. Cure 8 hours at 315°C (600°F).
4. Cool to room temperature in about 5 hours.

Material characterization tests were subsequently conducted with the follow-

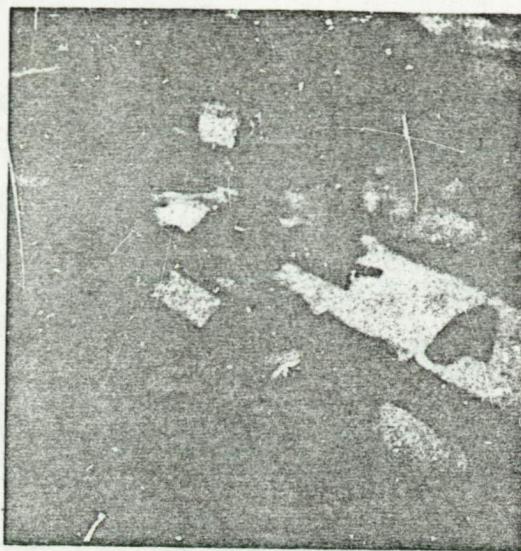


Figure 3.1. Pultrusion Bushing and Die Assembly Arrangement

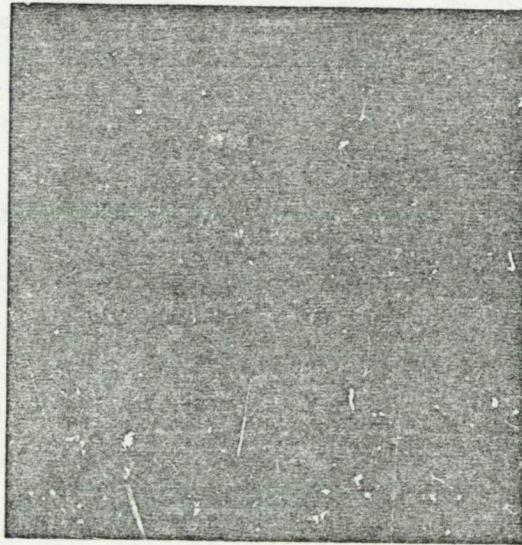


Figure 3-2. Pultrusion Die for 2.36mm (0.093 in.) Diameter Rod

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OF PULTRUDED PAGE 15
2026mm

ing results:

Density, gms/cc: 1.43 - 1.45
Resin Content, %: 28.6 - 28.9
Fiber, vol %: 54.3 - 55.4
Void Content, Vol %: 11.2 - 12.3

Photomicrographs were also made of transverse cross-sections of a typical sample of the HMS/NR150A2-060X rod. Typical samples of such photomicrographs are shown in Figure 3-3. The relatively high void content (11.2% - 12.3%) can be seen in Figure 3-3.

Samples from the post-cured rod stock were then evaluated for mechanical properties. Tensile and flexural tests were conducted with samples from the round rod, and good properties were displayed in both types of tests. Results from those tests are given in Table 1.

Table 1
FLEXURAL AND TENSILE PROPERTIES OF HMS/NR150A2-060X ROD

Sample No.	Flexural Modulus GN/m ² (psi)	Flexural Strength MN/m ² (psi)	Tensile Modulus GN/m ² (psi)
1	133.0 (19.3 x 10 ⁶)	669.5 (97,120)	---
2	148.9 (21.6 x 10 ⁶)	857.2 (124,134)	---
3	---	---	184.8 (26.8 x 10 ⁶)
4	---	---	174.4 (25.3 x 10 ⁶)

The fiber volume, discussed above, was relatively high, falling between 54.3 and 55.4 percent. This high fiber volume is judged to have contributed to the slightly higher modulus values obtained with the HMS/NR150A2-060X when compared with modulus data obtained in Phase I with HMS/P1700 pultruded rods. Fiber volume of the latter samples ranged from 50% to 54%, and the maximum tensile modulus was 158.6 GN/m² (23 x 10⁶ psi).

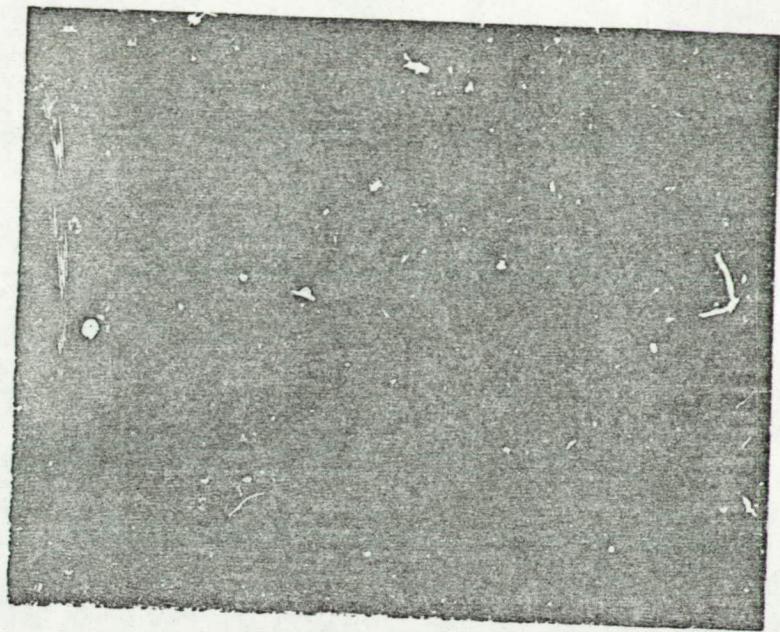


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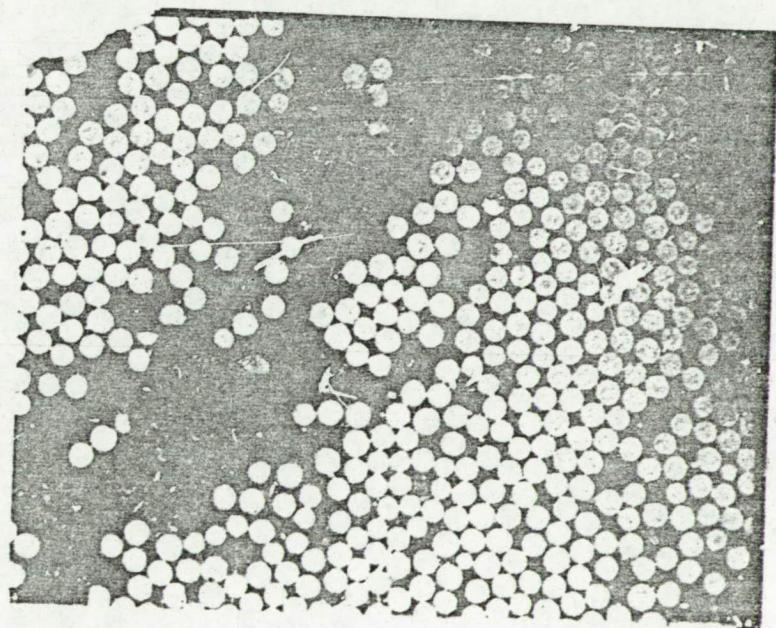


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Figure 3-3. Photomicrographs of HMS/NR150A2-060X Pultruded Rod Stock



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Figure 3-2. Photomicrographs of HMS/NR150A2-060X Pultruded Rod Stock (Continued)

Thermal control coatings were also evaluated for use with the HMS/NR150A2-060X high temperature rods. The finished rod stock was subjected to processing trials to check the compatibility and adherence characteristics of several candidate coatings selected to reduce structural temperature variations and thus permit longer structural life in the space environment. Candidate coatings evaluated were:

1. Aluminum platelets in polyurethane.
2. S13G/L0 (applied over a silicone primer).
3. Aluminum platelets in a silicone base resin.
4. S13G/L0 (applied over a dual primer).

Tests conducted in Phase IA were preliminary and were made to determine the coating adherence characteristics so as to eliminate coatings that tend to crack or chip when the rod is flexed for storage in canisters. In addition to determining adherence characteristics, the weight of each coating was determined to assess overall structural weight increases caused by coating application. If required, selected thermal control coatings will be tested further in Phase II to assess their effectiveness in reducing material degradation.

Four coating systems (Table 2) were obtained and applied to 20.3 cm (8.0 in.) lengths of rod stock. All test rods were cleaned with methyl ethyl ketone (MEK) and then primed to improve the adhesion of the coating. The primers used for each type coating are noted in Table 2. The first type of coating is a formulation made by the De Soto Company having aluminum platelets in an aliphatic polyurethane binder. The epoxy polyamide primer is also a De Soto product. The second coating system is an improved version of the NASA sponsored S13G coating developed by the Illinois Institute of Technology - Research Institute (IITRI). This system has been improved to provide lower outgassing and is now designated S13G/L0. The basic S13G/L0 system is a silicone binder pigmented with highly purified zinc oxide, and the low outgassing characteristics are achieved by vacuum reduction of the RTV 602 silicone binder. The third system is an ALCAN aluminum platelet type using

the General Electric RTV 602 silicone binder. The RTV 602 is the same binder used for the S13G/L0 but without vacuum reduction to minimize outgassing. This system was formulated in MDAC Laboratories and a 5 hour cure at 65°C (150°F) was used to assure complete cure. A subsequent trial of this system on an aluminum test panel indicated that cure could be achieved at room temperature without difficulty. The fourth system was similar to system No. 2 (Table 2) except for the use of an additional primer.

Table 2
SUMMARY OF PROTECTIVE COATINGS USED ON HMS/NR150A2-060X RODS

Note: All Rods Cleaned with MEK Prior to Application of Primer and Coating.

COATING SYSTEM	PRIMER	COATING	CURE	WEIGHT INCREASE ⁽¹⁾
1	Epoxy Polyamide (De Soto); Base: 513X332; Catalyst: 910X457	Aluminum Platelets in Polyurethane (De Soto); Base: 829X303, 37200, D3-8064; Catalyst: 910X376	Room Temp.	+0.38g (+30.4%)
2	Silicone (SS4044 Silane IITRI)	S13G/L0 (IITRI)	Room Temp.	+0.26g (+33.6%)
3	Silicone (SS4044 Silane)	Aluminum Platelets in RTV 602 Silicone; ALCAN MD 7100, 400 Mesh 17g powder in 100g resin	5 Hr. at 65°C	+0.25g (+20.0%)
4	Epoxy Primer Bostik Followed by Silicone Primer (SS4044 Silane); Epoxy Base: 463-12-8; Catalyst: CA-116	S13G/L0 (IITRI)	Room Temp.	+0.43g (+34.4%)

(1) Weight of basic 20.3 cm Rod = 1.25g (Avg.)
Weight increases shown are for 20.3 cm rod.

These coatings were selected to represent both low and high ratios of α_s/ϵ (solar absorptance to emittance). S13G can be considered the standard of the industry with respect to a flexible thermal coating with a low α_s/ϵ ratio. SS4044 Silane primer is normally adequate for the promotion of adhesion, but one set of samples was prepared with epoxy primer on the substrate. This choice was made because it was felt that an epoxy primer might offer better adhesion to the substrate than the silane primer. Tests showed approximately equal adhesion characteristics for either the single primer or dual primer approach.

The second type of coatings evaluated offered a low α_s , like S13G, but a high α_s/ϵ ratio. Binders were selected with respect to their potential for successfully bonding to the substrate. Urethane binders lack the long-term ultraviolet radiation resistance found in silicones such as RTV 602. The best ultraviolet radiation resistance would be obtained with potassium silicate, but coatings formulated with this material would be too brittle for this application.

Four samples are shown in Figure 3-4 along with coated plates that can be used to verify absorptivity and emittance characteristics of the coatings. All four samples were tested to check for any tendency of the coatings to crack or chip when the rods were flexed to simulate a 50.8 cm (20 in.) bend radius to simulate rod storage in canisters or the flexing of helix members in a geodetic beam. The radius chosen was based on not exceeding an outer fiber strain in the rod of 50 percent of the strain to failure. This criterion was chosen in initial design studies which are reported in Reference 2. All protective coating systems maintained good adherence, showing no signs of cracking when the rods were flexed to the specified radius.

3.2 THERMALLY INERT PULTRUDED ROD

To achieve pultruded rods that exhibit minimum thermal distortion, E-glass fibers were added to the basic HMS fibers to provide a near zero coefficient of thermal expansion (CTE) in the finished rod material. In such a hybrid

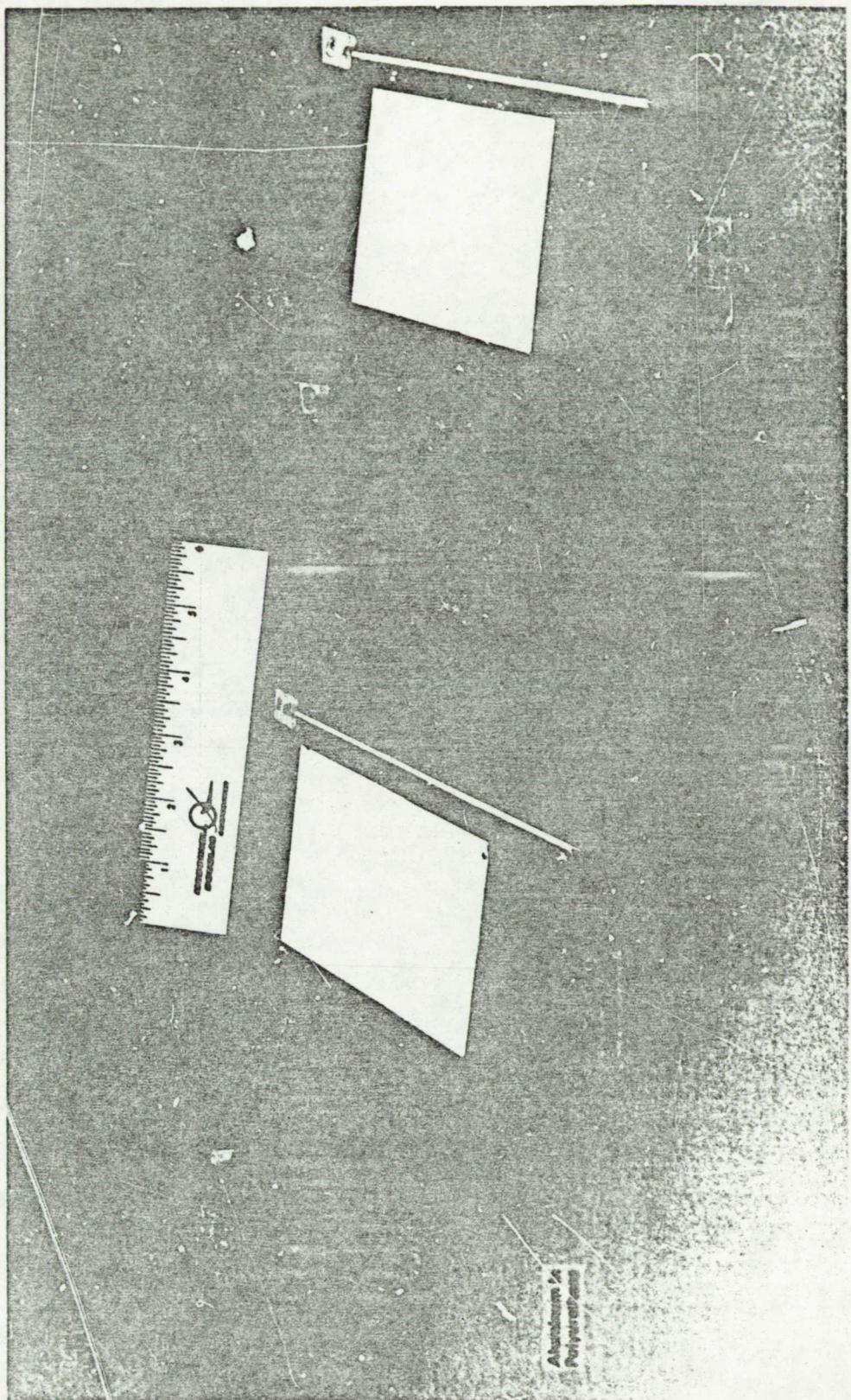


Figure 3-4. Graphite/Polyimide Pultruded Rod Samples with Protective Coatings

material, the positive CTE of the E-glass and resin matrix offset the negative CTE of the HMS fibers and provides a near zero CTE material. The required hybrid HMS/E-glass/P1700 material was obtained in prepreg form and subsequently pultruded into square cross-section rod with dimensions of 2.03 mm (0.080 in.) on each side. Pultrusion and testing of the near zero CTE rod stock was given high priority because it is a key initial step in verifying the feasibility of geodetic beams that can provide structures with minimum thermal distortion.

To obtain the required data, two 15.24 cm (6.0 in.) long samples were tested at Composite Optics Incorporated, San Diego, California. Each sample was tested between -184°C (-300°F) and +149°C (+300°F) with an initial test to determine thermal expansion without prior temperature excursions. The initial test was followed by ten cycles of temperature excursions between -184°C and +149°C without recording expansions. The thermal cycling was conducted at an average time rate of temperature change which resulted in a complete thermal cycle every 1.2 hours. Following the ten exposure cycles, each sample was again tested between -184°C and +149°C to determine expansion characteristics. Data from the tests are shown in Figures 3-5 and 3-6. The remeasurements of the thermal expansions following the thermal cycling yielded data which were in nominal agreement with the initial results. As shown in Figures 3-5 and 3-6, the coefficient of thermal expansion (CTE) between -46°C (-50°F) and 38°C (100°F) is very nearly zero, while a positive CTE occurs at temperatures up to 149°C and a negative CTE is evident at temperatures from -46°C to -184°C. An average CTE of $+0.198 \times 10^{-6}$ m/m/°C (0.11×10^{-6} in/in/°F), occurs between 24°C (75°F) and 149°C (300°F) and an average CTE of -0.144×10^{-6} m/m/°C (-0.08×10^{-6} in/in/°F) is seen for the temperature range from 24°C to -184°C. A small shift in the measured strain was seen after thermal cycling in each sample. However, the slopes and shape characteristics of the strain curves showed good consistency. Also, during each measurement cycle the data exhibited excellent repeatability at 24°C (75°F) which usually is indicative of a material which is dimensionally stable with respect to thermal cycling.

The results obtained from tests of the hybrid HMS/E-glass/P1700 rod stock showed that the hybridization approach to achieving near zero CTE characteristics is highly feasible. The rod samples tested had lower E-glass content (12.7% to 16.7%) than indicated to be required for zero CTE from analysis (18.8%). The

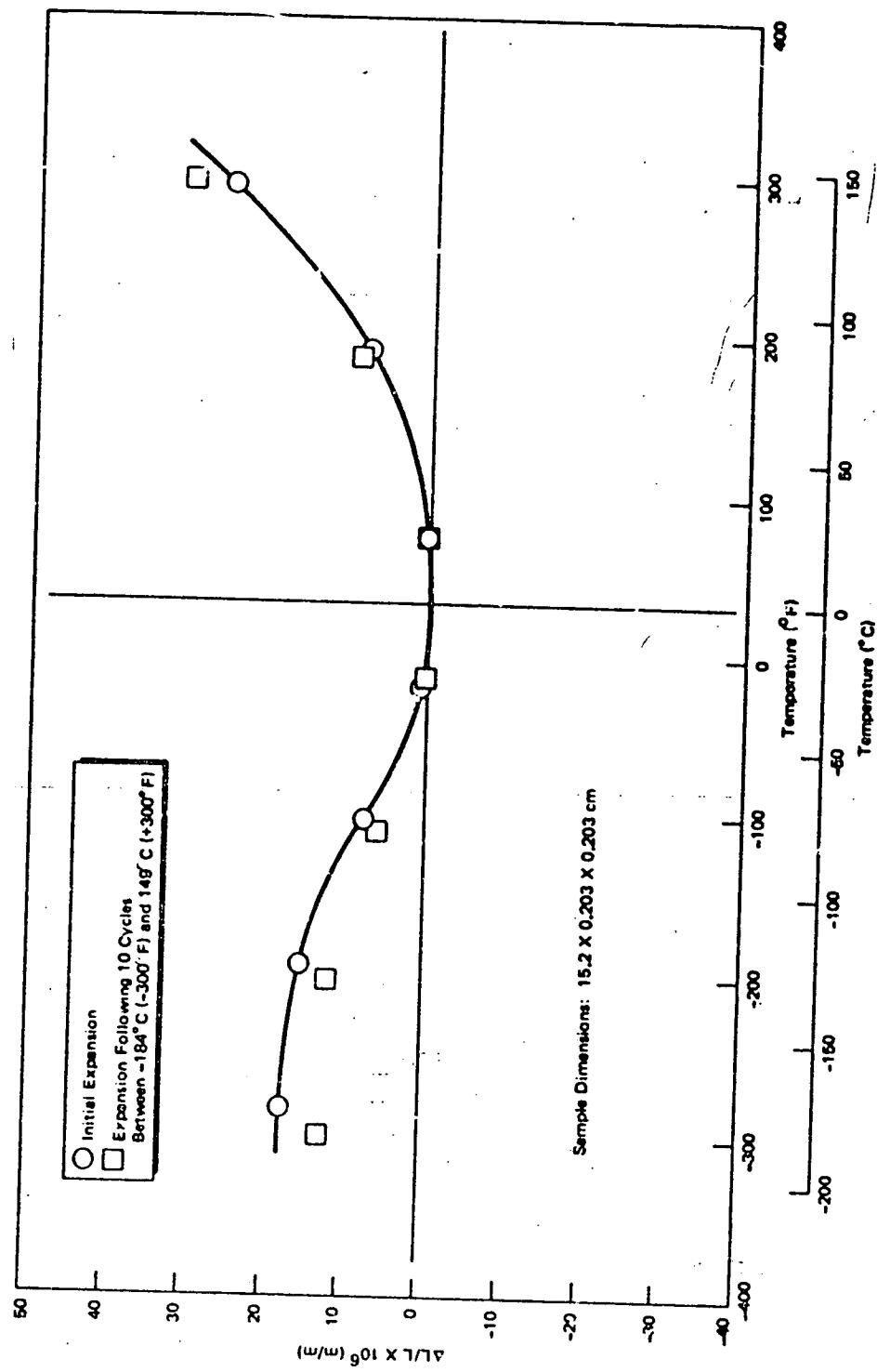


Figure 3-5. Thermal Expansion of Hybrid PMMA/E-Glass/P1700 Sample No. 1

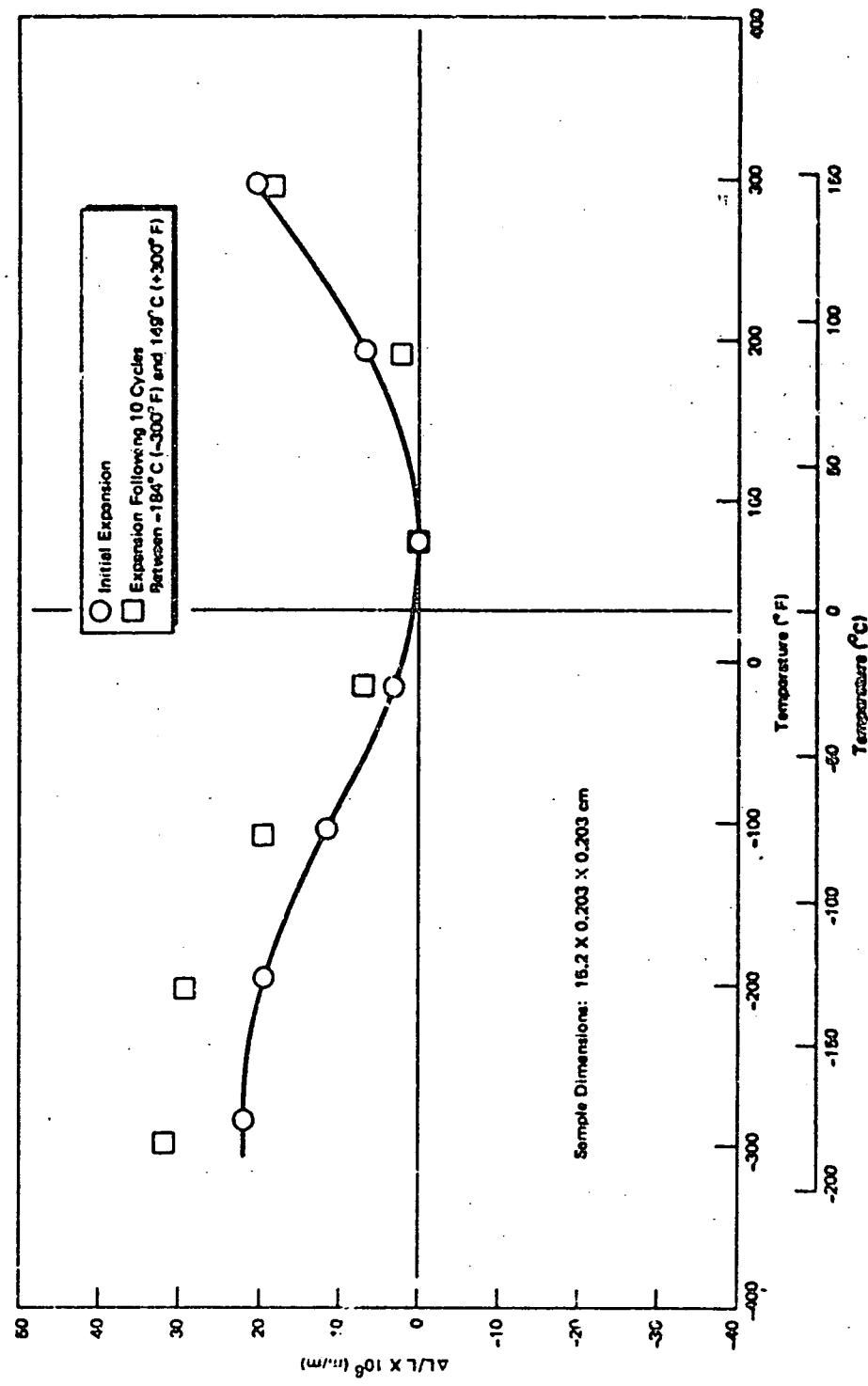


Figure 3-8. Thermal Expansion of Hybrid HMAS/E-Glass/P1700 Sample No. 2

near zero CTE values achieved with a lower than expected E-glass content is a desirable trend since higher modulus values are available with lower E-glass content.

Photomicrographs of a transverse section of the pultruded hybrid rod are shown in Figure 3-7. The light fiber ends seen in Figure 3-7 are the HMS fibers, while the dark fibers are the E-glass material. The nearly equal diameters of both types of fibers made it difficult to distinguish the two fibers and thus an acid etch that attacked only the E-glass fibers was used to define the material distribution shown in Figure 3-7.

The resin content, fiber content, void content, and density of three samples taken from the pultruded rod were as follows:

Sample No.	Volume Percent		Wt. Percent Resin	Void Content Volume %	Density g/cc
	E-Glass	HMS			
1	12.7	38.5	33.2	7.1	1.56
2	13.2	40.2	30.8	7.6	1.57
3	16.7	36.7	29.2	9.6	1.57

Tensile and flexure properties were also obtained from test samples taken from the hybrid rod. Those properties are shown in Table 3.

Table 3
TENSILE AND FLEXURAL PROPERTIES OF
HYBRID HMS/E-GLASS/P1700 ROD

Sample No.	Tensile Strength MN/m ² (psi)	Tensile Modulus GN/m ² (psi)	Flexural Strength MN/m ² (psi)	Flexural Modulus GN/m ² (psi)
1	771.4 (111,890)	128.2 (18.6 x 10 ⁶)	---	---
2	---	128.2 (18.6 x 10 ⁶)	---	---
3	---	---	803.5 (116,550)	109.6 (15.9 x 10 ⁶)
4	---	---	757.6 (109,890)	107.5 (15.6 x 10 ⁶)



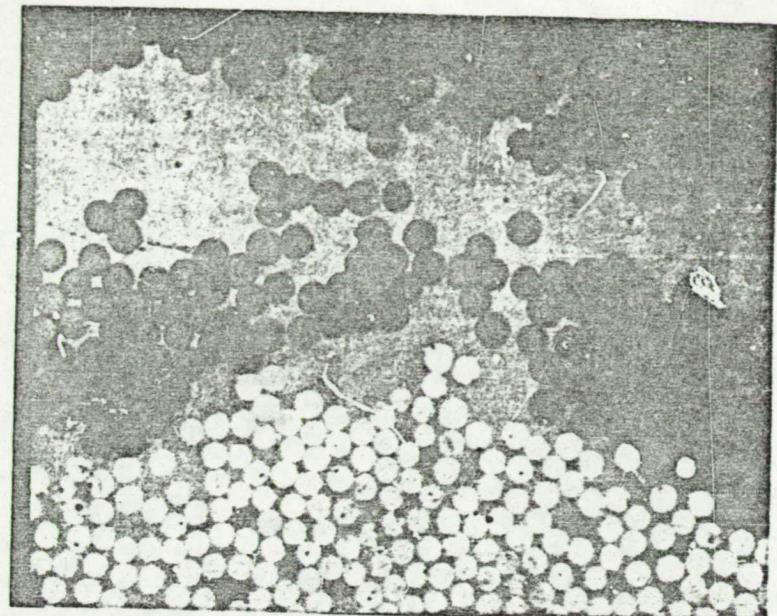
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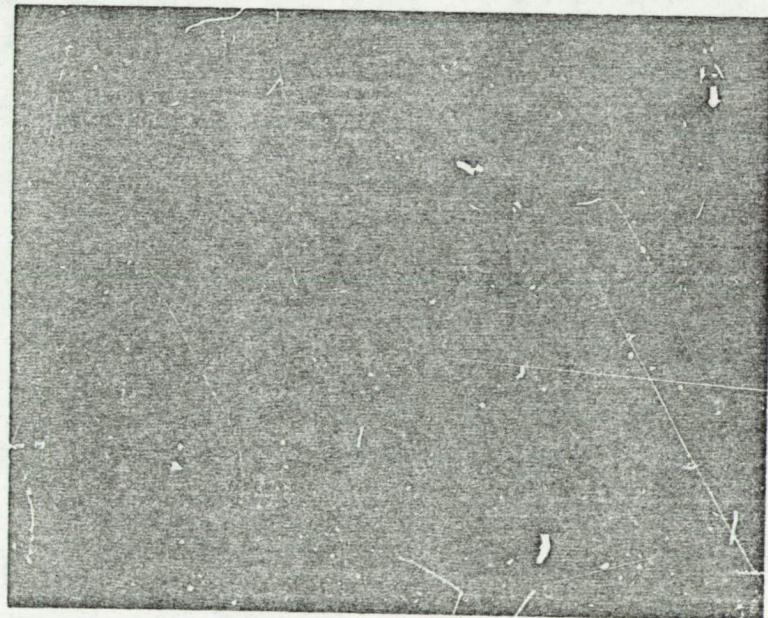
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Figure 3-7. Photomicrograph of Hybrid HMS/E-Glass/P1700 Rod Stock

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Figure 3-7. Photomicrograph of Hybrid HMS/E-Glass/P1700 Rod Stock (Continued)

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3.3 SMALL DIAMETER PULTRUDED ROD

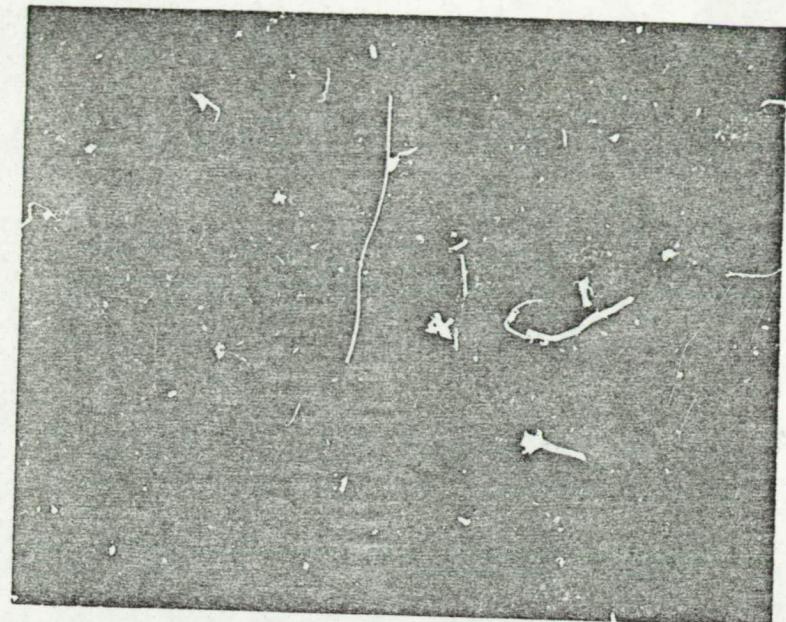
Small diameter pultruded rods will be required for lightly loaded geodetic beams that have relatively small diameters, e.g., 45.7 cm (18 in.) to 101.6 cm (40 in.) in diameter. Thus, an experimental effort to pultrude 0.89 mm (0.035 in.) diameter rod stock made from HMS/P1700 was undertaken and successfully completed. Four steel bushings and a final sizing die with a teflon insert were used in pultruding the small diameter rods. All four bushings were held at 399°C (750°F) while the final sizing die was held at 232°C \pm 14°C (450°F \pm 25°F). A maximum pultrusion rate of 38.1 cm/min (15 in/min) was used to produce satisfactory rod stock. Above that speed the prepreg tape material would spiral in the bushings and die, thus causing twisted stock to be produced. Bushing sizes were 2.36 mm (0.093 in.), 1.85 mm (0.073 in.), 1.32 mm (0.052 in.), and 1.04 mm (0.041 in.). Approximately 30.5 m (100 ft) of the small diameter HMS/P1700 rod was produced by CEC.

Tensile and flexural properties were obtained from test samples taken from the small diameter rods. Data from those tests are presented in Table 4.

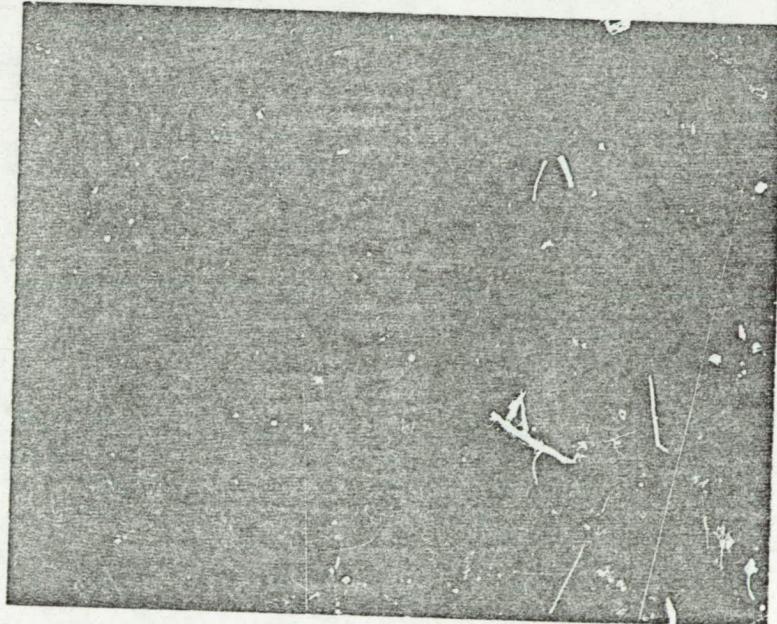
Table 4
TENSILE AND FLEXURAL PROPERTIES OF
SMALL DIAMETER HMS/P1700 ROD

Sample No.	Tensile Modulus GPa/m ² (psi)	Flexural Strength MN/m ² (psi)	Flexural Modulus GPa/m ² (psi)
1	198.2 (28.75 x 10 ⁶)	---	---
2	191.3 (27.75 x 10 ⁶)	---	---
3	---	1,413.3 (205,050)	190.3 (27,61)
4	---	90.14 (130,700)	167.8 (24.34)

Photomicrographs were also made of transverse sections taken from rod samples (Figure 3-8). Good uniformity of fiber distribution can be noted in Figure 3-8.



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Figure 3-8. Photomicrographs of 0.89mm Diameter HMS/P1700 Pultruded Rod

The successful production of the 0.89 mm diameter pultruded rod stock demonstrates the feasibility of producing rods small enough to fabricate smaller diameter geodetic beams. Geodetic beams of smaller diameters (45 to 100 cm) will be required in certain space structures such as small platforms and in lightly loaded truss members.

Section 4

ADVANCED JOINT ENCAPSULANT MATERIALS

The development of long life pultruded rod material with service temperature capability up to the range of 204°C (400°F) to 260°C (500°F) require similar capability in joint encapsulant materials. Accordingly, evaluations of encapsulant materials with higher temperature capabilities than the Versimid 1200 were undertaken as an extension of the Phase I joining investigations. Versimid 1200, a polyamide material used in Phase I test cylinders, has a service temperature of approximately 163°C (325°F). To maintain comparative test evaluations, Versimid 1200 was retained in the Phase IA testing of encapsulant materials.

As a first step in encapsulant evaluations, a survey of candidate materials was made. This survey resulted in the selection of the materials shown in Table 5.

Table 5
CANDIDATE ENCAPSULANT MATERIALS

Material Designation	Material Type	Service Temperature	Mold Injection Temperature
Versimid 1200	Polyamide	163°C (325°F)	260°C (500°F)
VAR 4032	Polyester	204°C (400°F)	329°C (625°F)
VAR 6019	Polyester	204°C (400°F)	246°C (475°F)
Upjohn 2080	Polyethersulfone	232°C (450°F)	399°C (750°F)
JF-1008	Polyethersulfone	232°C (450°F)	399°C (750°F)
OF-1008	Polyphenylsulfide	232°C (450°F)	399°C (750°F)

Encapsulant tests were initially conducted to define injection temperature and pressure requirements for each material. Acquisition of such data was considered an essential step since excessive temperature and pressure requirements could cause excessive power usage in orbital operations of the beam builder. Thus, materials requiring excessive power may be eliminated through initial screening tests.

All materials were received in cylindrical pellet form, pellet dimensions ranging from approximately 3.0 mm (0.12 in) in diameter by 6.4 mm (0.25 in) in length to 6.4 mm (0.25 in) in diameter by 12.8 mm (0.50 in) in length. The pellets were first tested at atmospheric pressure to determine if heating at relatively low pressure could be used to melt and then resolidify the encapsulant material into cylindrical slugs sized to fit in the receptacle of a hot-melt injection gun. Such initial tests were successful with Versimid 1200, VAR 4302 and VAR 6019. The successfully molded VAR 4302 and VAR 6019 slugs are shown in Figure 4-1. Further trials were conducted using a heated mold which could be pressurized. The test equipment used for this phase of testing is shown in Figure 4-2. The temperature used for Upjohn 2080, JF-1008, and OF-1008 was 343°C (650°F) and the pressure was 17.2 MN/m² (2,500 psi). None of these three materials could be melted and resolidified at that temperature/pressure combination. Figure 4-3 shows failure of the Upjohn 2080 material pellets to flow, the resulting slug retaining the original form of compacted pellets that crumbled apart when handled.

The VAR 4302 and VAR 6019 slugs were subsequently tested for use in the hot melt injection gun. The current gun configuration has a temperature capability of 246°C (475°F) for melting the resin slug. This temperature proved satisfactory for the VAR 6019 and Versimid 1200 materials, but was not sufficient to cause the VAR 4302 to flow. A test joint (Figure 4-4) was made using the VAR 6019 material in the hot-melt injection gun to join three HMS/NR150A2-060X pultruded rods. Chopped graphite fibers (10% by weight) were mixed with the VAR 6019 and VAR 4302 pellets during the molding process, thus providing finished slugs containing dispersed fibers.

The limited temperature capability of the current hot-melt injection gun restricted fabrication of test joints to those made with VAR 6019 and Versimid 1200 materials.

Initial samples of both types of encapsulated joints were fabricated using HMS/NR150A2-060X rods. The sample encapsulated joints were then tested to determine out-of-plane joint stiffness for each of the encapsulant materials. Results of those tests are shown in Figure 4-5. The local spring

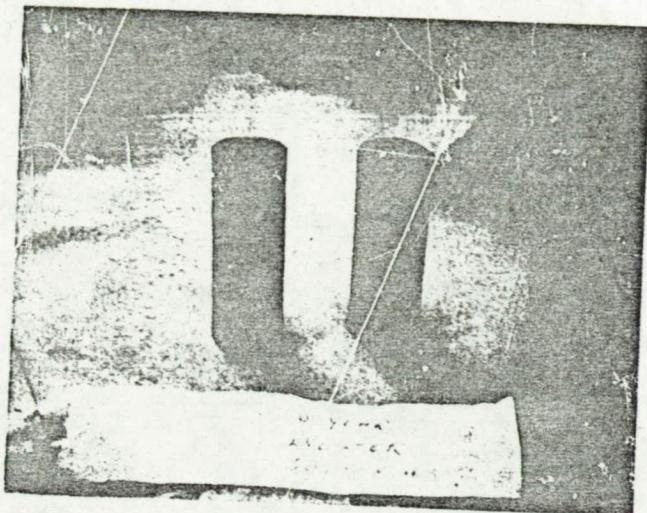


Figure 4-1. Successfully Molded VAR 4302 and VAR 6019 Slugs

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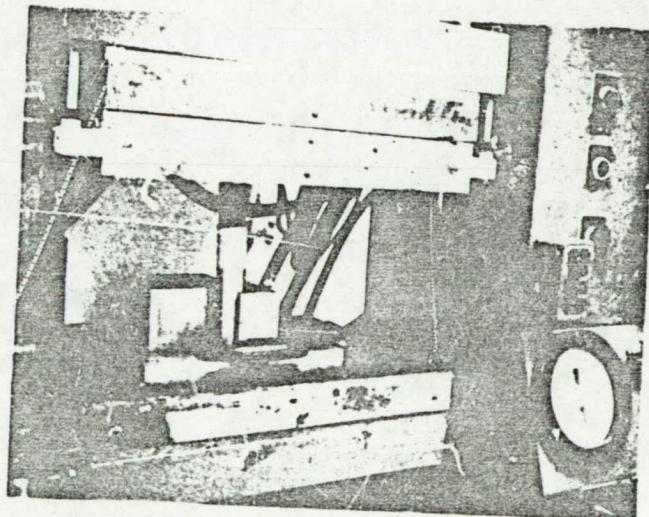
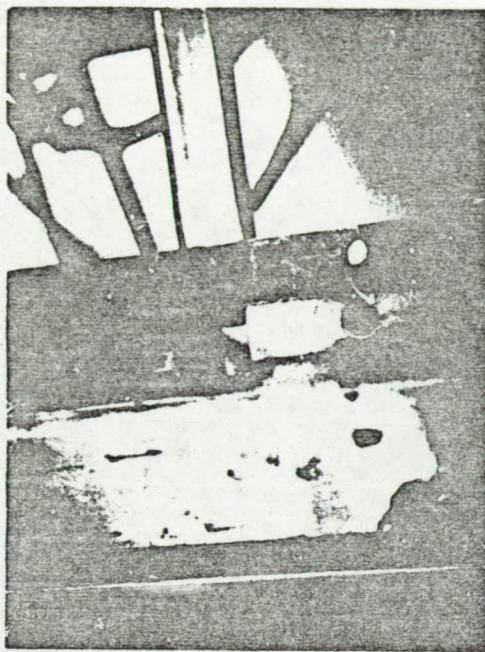
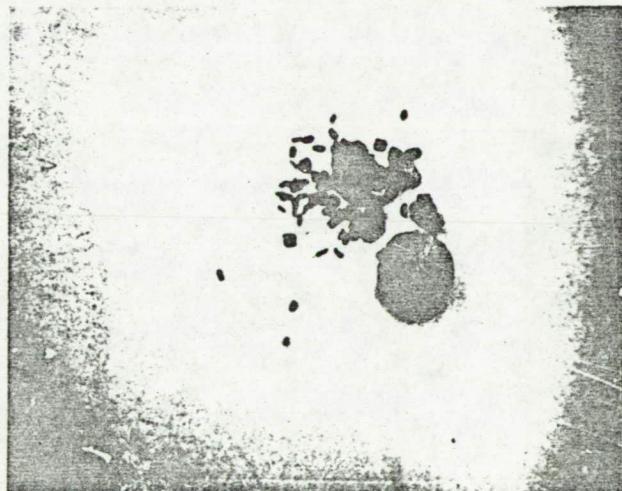


Figure 4-2. Heated and Pressurized Mold for Forming Cylindrical Slugs of Encapsulated Material



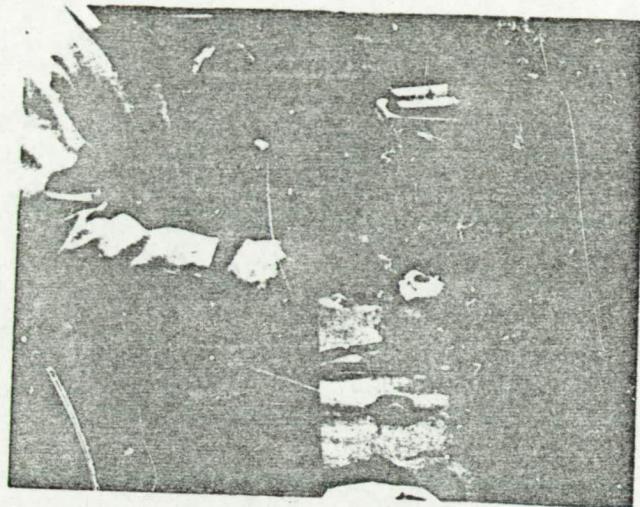
a. Removal of Resin Slug



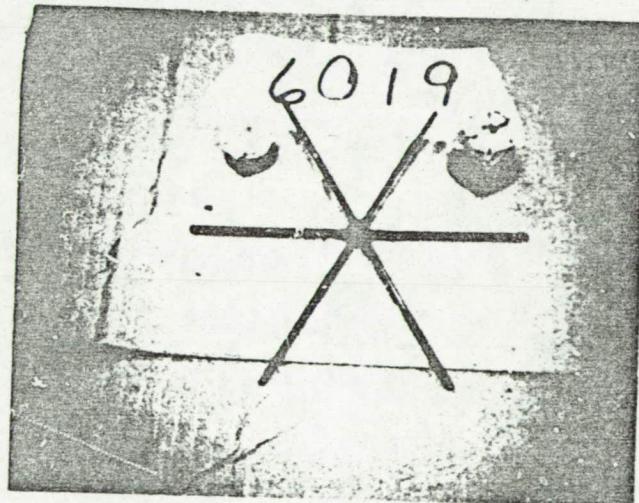
b. Unsolidified Slug

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Figure 4-3. Pressurized Molding Trials with UpJohn 2080; Pressure = 17.2 MN/m^2 , Temperature = 343°C



a. Hot Melt Injection Gun with VAR 6019



b. Completed Joint

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Figure 4-4. Encapsulated Joint Made with VAR 6019

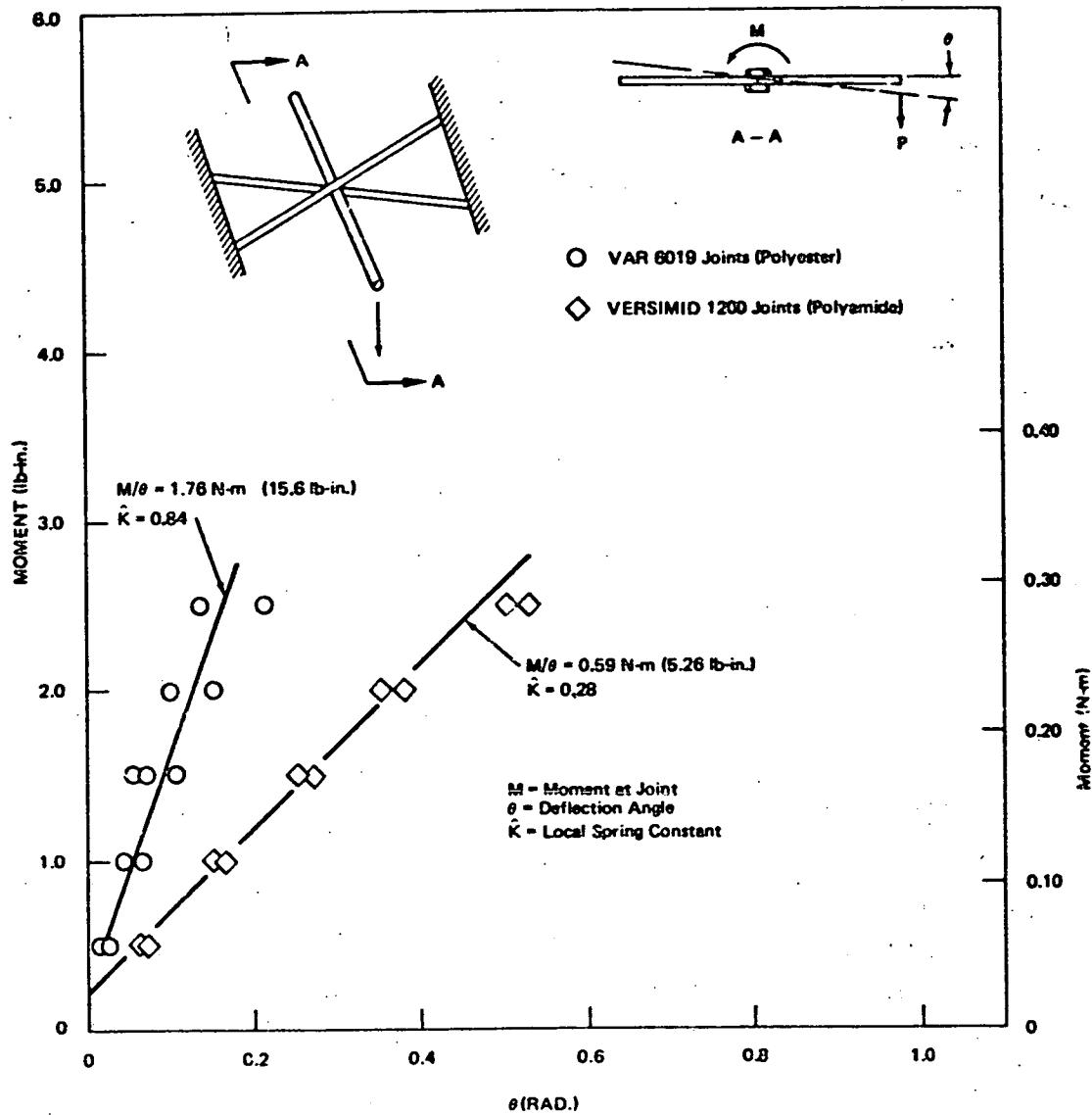


Figure 4-5. Moment vs. Deflection for Round Rods Encapsulated with Versimid 1200 or VAR 6019

constant, \hat{K} , obtained from the test data in Figure 4-5 are lower than obtained earlier in Phase I with Versimid 1200 encapsulated joints using HMS/P1700 rods. However, fairly wide ranges of \hat{K} determined in Phase I did not significantly change the local buckling coefficient, C (Reference 2).

Results of the encapsulant evaluations showed that polyester systems (VAR 4302 and VAR 6019) were capable of being formed into slugs or rods that can be fed through hot-melt injection equipment. Satisfactory joints were made from VAR 6019 material, as well as Versimid 1200. In contrast, Upjohn 2080, JF-1008, and OF-1008 were not successfully consolidated from the as-received pellet form to a slug or rod shape that can be used in hot-melt injection equipment. Those materials would require additional evaluations to fully determine their suitability as encapsulant materials for high temperature service conditions in geodetic beams.

Section 5 CONCLUSIONS AND RECOMMENDATIONS

This section presents the conclusions reached as a result of the work conducted in Phase 1A. Also, recommendations for Phase II, as affected by Phase 1A efforts, are made.

5.1 CONCLUSIONS

The following conclusions regarding beam attach concepts, long life material, and advanced joint encapsulant materials are presented based upon the work reported in Sections 2, 3, and 4.

Geodetic Beam Local Attachments

1. Design studies showed the geodetic beam to be versatile in various structural arrangements requiring local beam-to-beam attachments that will be required in near-term large space systems.
2. Use of external elliptical frames provides a significant range of angular intersections for the geodetic beam.
3. Foldable cradles offer a lightweight, compact, highly rigid arrangement for joining crossing geodetic beams.
4. Frames and fittings can be easily attached to node positions on the geodetic beam for use in equipment attachment, cable attachments, or beam-to-beam joining.

Long Life Material

1. High temperature HMS/NR150A2-060X round rod stock was successfully pultruded using steel bushings and a steel die at 427°C (800°F). Approximately 80 linear feet of rod stock was pultruded at a speed of 3.8 cm per minute (1.5 in/min.).
2. The short time at elevated temperature during pultrusion resulted in partial cure, necessitating post-cure of the rods after pultrusion.
3. High tensile and flexural modulus values were exhibited by the post-cured rods. Tensile modulus averaged 179.6 GN/m^2 ($26.1 \times 10^6 \text{ psi}$) and flexural modulus averaged 141 GN/m^2 ($20.4 \times 10^6 \text{ psi}$).

4. All four protective coatings evaluated with the HMS/NR150A2-060X rods showed good adhesion with no tendency to chip or crack when the rods were flexed to simulate canister storage or helix radii in geodetic beams.
5. Hybrid pultruded rod stock (HMS/E-glass/P1700) was demonstrated to have a low coefficient of thermal expansion ($<0.20 \times 10^{-6}$ m/m/°C or $<0.11 \times 10^{-6}$ in/in/°F) in the range of -184°C (-300°F) to +149°C (+300°F).
6. Pultrusion of 0.89 mm (0.035 in.) diameter rod stock was successfully demonstrated using HMS/P1700 prepreg material.

Advanced Joint Encapsulant Materials

1. Encapsulated joints were successfully demonstrated with a high temperature polyester material (VAR 6019) having a service temperature capability of 204°C (400°F).
2. Satisfactory strength and stiffness characteristics were exhibited in tests of the joints made from VAR 6019.

5.2 RECOMMENDATIONS

The following recommendations for Phase II activities are based on results of Phase 1A work.

1. The use of hybrid HMS/E-glass/P1700 rod material is recommended for Phase II test articles because of its low CTE characteristics and because of the large percentage of large space structures having temperatures in a range permitting use of the P1700 resin system. This recommendation is reinforced by the necessity to postcure the HMS/NR150A2-060X rod stock after pultrusion. Also, the notification by duPont that NR150 series resins are no longer available would necessitate development of another high temperature pultruded rod material.
2. In keeping with the use of HMS/E-glass/P1700 rod material, it is recommended that Versimid 1200 polyamide be used for joint encapsulation.

Section 6
REFERENCES

1. Space Construction System Analysis. Part II Mid-Term Briefing, Contract NAS9-15718, 16 October 1979.
2. Development of a Composite Geodetic Structure for Space Construction. Phase I Final Report. Contract NAS9-15678, October 1979.

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